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Flue Gas Desulfurization Pilot Study. Phase I Survey of Major Installations. Appendix 95-E Limestone/Gypsum Flue Gas Desulfurization Process

NATO Committee on the Challenges of Modern Society, Brussels (Belgium)

Jan 79

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COMMITTEE ON THE CHALLENGES
OF MODERN SOCIETY

Flue Gas Desulfurization Pilot Study Phase I — Survey of Major Installations - Limestone/Gypsum Flue Gas Desulfurization Process

Appendix 95-E

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PHASE I

Flue Gas Desulfurization Pilot Study Phase I

Survey of Major Installations - Limestone/ Gypsum Flue Gas Desulfurization Process

APPENDIX 95-E

Lead Country - United States

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SUMMARY

The limestone/gypsum flue gas desulfurization system has proved reliable in controlling SO_2 emissions from large boilers and producing a salable, wallboard-quality gypsum. This process has been the most popular FGD system in Japan; however, few new systems are being installed since fuel oil desulfurization has become more cost-competitive, ambient air SO_2 levels have declined, and gypsum supplies are abundant.

Limestone/gypsum systems in Japan have been developed to nearly 100 percent availability, about 90 percent average SO_2 removal efficiency, and very high limestone utilization. Most mechanical problems that initially plagued these systems have been solved, and although not fully tested, some success has been reported on high-sulfur applications. Most systems have extensive automatic controls capable of regulating as many as six or seven variables.

Limestone/gypsum scrubbers are best suited for areas where land is scarce, limestone is readily available, and gypsum is in demand.

The advantages and disadvantages of the limestone/gypsum FGD system are as follows:

Advantages

(1) The basic process is fairly simple and contains few steps.

(2) Capital and operating costs are relatively low, and limestone is fairly abundant in many countries.

(3) Sulfur dioxide removal efficiencies are generally high, about 95 percent.

(4) The two-stage treatment of flue gases permits simultaneous removal of SO_2 and particulates.

(5) The process is one of the most common methods used by utilities to control SO_2 emissions, aside from firing low-sulfur fuel. Because commercial installations have been operating for more than 4 years, this is one of the more fully understood FGD processes. Operational experience has given a greater understanding of basic principles.

(6) Successful performance has been demonstrated, particularly in terms of SO_2 removal on coal-fired systems.

(7) The product, gypsum, is salable or is suitable for landfill.

Disadvantages/Problems

(1) If not designed carefully or operated attentively, limestone systems have a tendency to chemical scaling, plugging, and erosion, which can halt operation.

(2) Fly ash and chloride affect product quality.

1.0 BACKGROUND AND INTRODUCTION

This report is one of a series on the status of flue gas desulfurization (FGD) processes in the NATO countries and Japan. In this program the United States, the Federal Republic of Germany, and Norway each acted as lead countries in gathering information and preparing reports on selected FGD processes.

The limestone/gypsum process is a wet scrubbing system in which a mixture of finely crushed limestone ($CaCO_3$) and water is intimately contacted with the boiler flue gases in an absorption tower. The SO_2 in the flue gas reacts with the limestone to form calcium-sulfur compounds. The gas and liquid slurry are separated, and the slurry is further reacted with oxygen to form gypsum. The resulting gypsum is dewatered to form a salable by-product or can be readily used as landfill.

The limestone/gypsum process is an alternative to the limestone/sludge system when gypsum is desired as a salable by-product, where land for disposal is scarce, or where a more stable landfill is required. This process was developed in Japan where the gypsum can be sold and land is scarce.

Operation of the first limestone/gypsum unit began in 1973 at Jujo Paper, Akita, Japan. The flue-gas volume cleaned at this location is 84 x 10^3 Nm^3/h. A year later two power plants, one paper mill boiler, and one chemical company boiler started operating limestone/gypsum scrubbers to control SO_2 emissions. Sixteen more systems were put in operation in 1975 and an additional 19 in 1976, all in Japan. This process has virtually replaced the lime/gypsum process, which once was the system of choice for large boilers in Japan.

As of December 1977, 23 limestone/gypsum systems were in operation at Japanese utilities, serving 5511 MW of electrical-generating capacity.

The rapid growth of FGD systems in Japan came about as a result of the reliability of their operation and the economic advantage they offer over the burning of low-sulfur fuels as a means of controlling SO_2. The growth rate may decline after 1977, however, for the following reasons:

1. Ambient SO_2 concentrations in large cities and industrial districts have decreased to a range of 0.02 to 0.03 ppm, almost meeting the ambient air standard.

2. New-plant construction has decreased.

3. New markets for gypsum are small, and a decrease in the price difference between high-sulfur and low-sulfur oils have started a trend toward the use of low-sulfur fuels.

4. Several processes for simultaneous removal of NO_x and SO_2 have been developed, and industry is waiting for this technology to be developed further.

2.0 GENERAL PROCESS DESCRIPTION

The basic principles are essentially the same for all limestone systems. A limestone-water slurry is contacted with flue gas containing SO_2. The SO_2 transfers into the slurry and reacts with the limestone. The by-products are calcium sulfite hemihydrate and gypsum. Calcium sulfite hemihydrate is further oxidized to gypsum. The gypsum is either dewatered and used as landfill, or sold. Figure 1 is an example of a flow diagram and material balance of a 500 MW coal-fired boiler with a limestone/ gypsum FGD system.

2.1 PROCESS CHEMISTRY

The overall reactions that take place in the absorber are as follows:

$$SO_2 + CaCO_3 \rightarrow CaSO_3 + CO_2 \quad (1)$$

$$SO_2 + 1/2\ O_2 + CaCO_3 \rightarrow CaSO_4 + CO_2 \quad (2)$$

Reaction 2 results in gypsum; however, there are many intermediate steps. The calcium cation is formed during slurry preparation.

$$CaCO_3(s) \rightarrow CaCO_3(aq) \quad (3)$$

$$CaCO_3(aq) \rightarrow Ca^{++} + CO_3^{-} \quad (4)$$

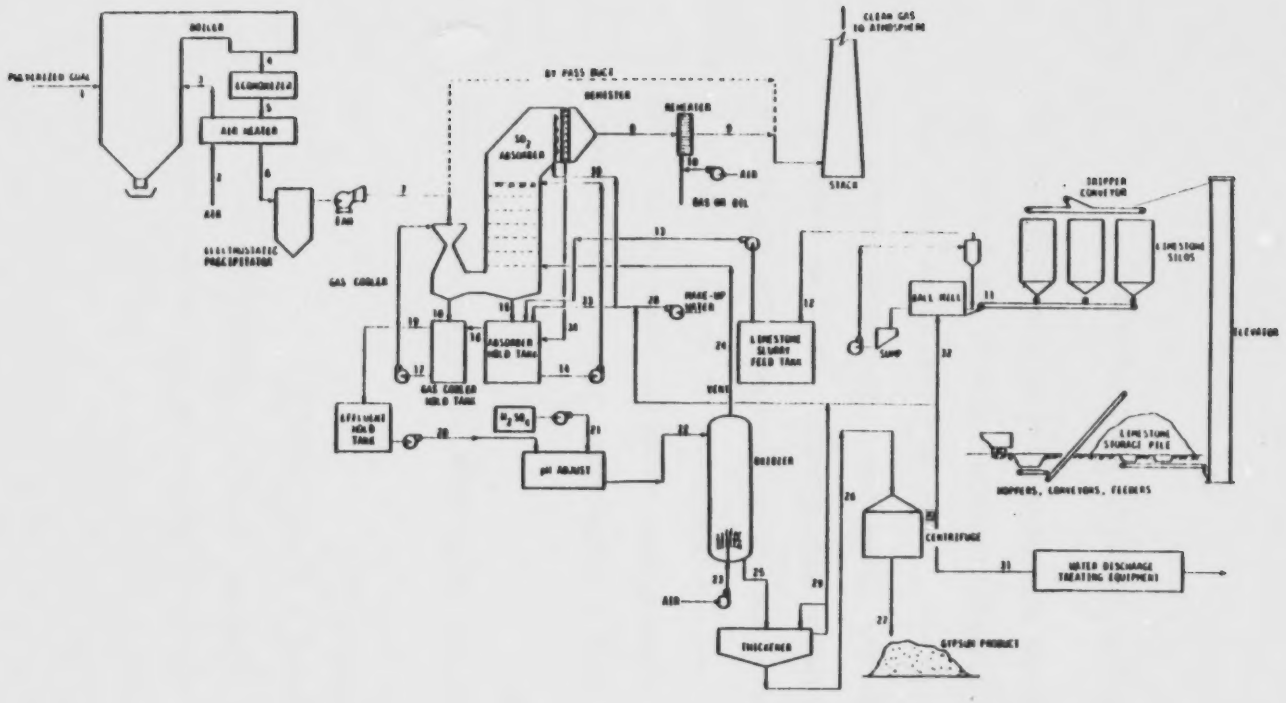

Figure 1. Example limestone/gypsum process flow diagram and material balance as applied to a 500-MW coal-fired boiler. (See notes at end of figure.)

(continued)

Stream No.	1	2	3	4	5	6	7	8
Description	Coal to boiler	Combustion air to air heater	Combustion air to boiler	Flue gas to economizer	Flue gas to air heater	Flue gas to ESP	Flue gas to gas cooler	Flue gas to reheater
Rate, 1000 kg/h	170	2,049	1,848	1,998	1,998	2,198	2,198	2,354
Nm^3/s		403	371	394	394	434	485	494
m^3/s Liquid								
Particulates, kg/h				15,300	15,300	15,300	14	7
Temperature, °C		43	279	477	274	154	154	52
Specific gravity								
Viscosity, Pascal-seconds								
Undissolved solids, %								
pH								
Sulfur balance as SO_2, kg/h		0	0	11,335	11,335	11,335	11,335	1,134

Stream No.	9	10	11	12	13	14	15	16	17
Description	Flue gas to stack	Hot gas to reheater	Limestone to ball mill	Slurry to feed tank	Slurry to absorber hold tank	Slurry to absorber	Spent slurry to hold tank	Slurry to gas cooler hold tank	Slurry to gas cooler
Rate, 1000 kg/h	2,402	48	22	36	36	21,756	21,898	144	18,333
Nm^3/s									
m^3/s liquid				0.006	0.006	5.8	6.0	0.009	4.85
Particulates, kg/h	7	0							
Temperature, °C	73	1074							
Specific gravity				1.65				1.05	
Viscosity, Pascal-seconds									
Undissolved solids, %				60					
pH					7.2	~7.0			
Sulfur balance as SO_2, kg/h	1,134	0	0	0	0			10,102	

Figure 1 (continued).

(continued)

Stream No.	18	19	20	21	22	23	24	25	26
Description	Spent slurry to hold tank	Spent slurry to E.H.T.	Slurry to pH adjust	H_2SO_4 addition	Slurry to oxidizer	Air to oxidizer	Oxidizer vent to absorber	Slurry to thickener	Thickener solids to centrifuge
Rate, 1000 kg/h	18,235	229	229	0.102	229.1	66	64	231	105.7
Nm^3/s						14.2,	13.8		
m^3/s liquid	4.85	0.06	0.06		0.06			0.06	
Particulates, kg/h									
Temperature, °C						43			
Specific gravity									
Viscosity, Pascal-seconds									
Undissolved solids, %								13.7	30
pH					3.5				
Sulfur balance as SO_2, kg/h		10,302	10,302		10,302		100	10,202	10,202

Stream No.	27	28	29	30	31	32	33	34	35
Description	Gypsum product	Fresh water makeup	Thickener overflow	Centrifuge liquor discharge	Purge water	Water to ball mill	Water to absorber hold tank	Demister return	Demister feed
Rate, 1000 kg/h	35.2	240	125.3	70.5	13.6	14	140	160	148
Nm^3/s									
m^3/s liquid			0.034				0.04	0.04	0.04
Particulates, kg/h									
Temperature, °C									
Specific gravity			1.0	1.0					
Viscosity, Pascal-seconds									
Undissolved solids, %	90		0	0					
pH									
Sulfur balance as SO_2, kg/h	10,202	0	0	0	0	0			

NOTES:

1 Calculations based on:

a. 120% stoichiometric limestone: 90% $CaCo_3$ (dry), 5% H_2O.
b. 3.5% sulfur in coal (dry).
c. 12% ash coal (as fired).
d. 75% of ash in coal evolves as fly ash.
e. 99.5% removal of particulates to scrubber.
f. 90% SO_2 removal.

2 Particulates should be added to gas to get total stream rate.

Figure 1 (continued).

The sulfite (SO_3) anion forms at the flue gas slurry interface in the absorber.

$$SO_2(g) \rightarrow SO_2(aq) \quad (5)$$

$$SO_2(aq) + H_2O \rightarrow H_2SO_3^{=} \rightarrow HSO_3^{=} + H^+ \quad (6)$$

$$HSO_3^- \rightarrow H^+ + SO_3^{=} \quad (7)$$

The sulfite ion (equation 7) then combines with the calcium ion (equation 4) to form the precipitate calcium sulfite hemihydrate (equation 8).

$$Ca^{++} + SO_3^{=} + 1/2\ H_2O \rightarrow CaSO_3 \cdot 1/2\ H_2O(s) \quad (8)$$

The production of gypsum is suppressed in the absorber to reduce scaling. The sludge containing $CaSO_3 \cdot 1/2\ H_2O$ is sent to an oxidizer to form gypsum by the following reaction:

$$CaSO_3 \cdot 1/2\ H_2O + 1/2\ O_2 + 3/2\ H_2O \rightarrow CaSO_4 \cdot 2H_2O$$

After the gypsum is washed and dewatered to a water level of approximately 8 percent, it is ready to be marketed.

Based on the molecular weights of limestone and SO_2, the theoretical requirement is 1 mol (100 g/g mol) limestone per mol of SO_2 (64 g/g mol) removed. Assuming a 1.05 excess stoichiometric requirement and 95 percent purity of limestone, actual limestone required is

$$\frac{100}{64} \times \frac{1.05}{0.95} = 1.72 \text{ kg/kg } SO_2 \text{ Removed}$$

If the by-product gypsum (172 g/g mol) is assumed to be 98 percent pure with 8 percent retained water, the by-product

generated can be calculated by considering molecular weights.

$$\text{gypsum} = 1.08 \times 1.05 \frac{(0.98 \times 172 + 0.02 \times 100)}{64} = 3.022 \text{ kg/kg of } SO_2 \text{ Removed}$$

2.2 DESCRIPTION OF EQUIPMENT COMPONENTS

2.2.1 Primary Particulate Removal

The primary particulate-removal device on coal-fired power plants can be either a venturi scrubber or an electrostatic precipitator (ESP). On oil-fired boilers an ESP is used. An ESP removes particulates from the flue gas before it enters the scrubber. Particulate matter in the by-product gypsum reduces the quality of the gypsum. In some units, such as the boilers at the Isogo plant of Electric Power Development Company, an ESP is followed by two SO_2 scrubbers in series. Most of the product gypsum is discarded, but some is sold for cement. In most of the existing systems, fly ash is removed before scrubbing to produce a high-quality gypsum.

2.2.2 Gas Cooler

On oil-fired boilers, flue gas is cooled and humidified by contact with water before it enters the scrubber. Cooling the gas improves the SO_2 removal rate and protects plastic packings and coatings. Cooling and humidifying the gas also apparently reduces deposits and scaling in the scrubber. When there are two scrubber units, the first scrubber takes

the place of the gas cooler. The second scrubber, or absorber, is the primary SO_2 removal unit in the system and is designed to provide intimate contact between the flue gas and the slurry.

2.2.3 SO_2 Absorber

Scrubber design varies among the processes. At Mitsubishi-JECCO, the scrubber is a spray tower packed with plastic (Figure 2). A venturi is used at Chemico-Mitsui, Chemico-IHI, and Mitsui Miike, a turbulent contact absorber (TCA) with polyethylene balls at Ishikawajima (Figure 3), a stainless steel screen-type at Chubu-Mitsubishi Chubu-MKK (CM) (Figure 4), and perforated plates at the Babcock-Hitachi and Sumitomo-Fuji Kasui processes (Figure 4). The reliability of the Mitsubishi-JECCO packed tower and Chemico venturi scrubber has been well demonstrated in Japan. The former has less pressure drop. The TCA scrubber at Ishikawajima has a high SO_2 removal efficiency, but presents the problem of ball wear. The perforated plate scrubber at the Sumitomo-Fuji Kasui process (Moretana type) is designed to provide extreme turbulence and produce foam layers 38 to 50 cm thick. High SO_2 removal efficiency is attained during the formation of heavy mist.

At the Chemico-Mitsui, Chemico IHI, and Mitsui Miike processes which use no prescrubbers or coolers, the absorber

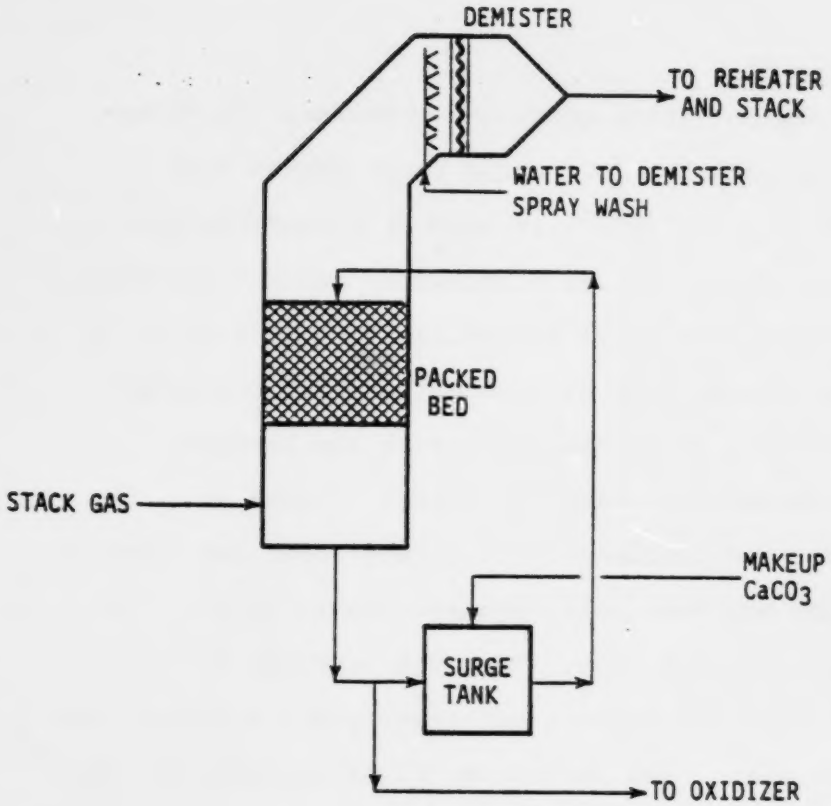

Figure 2. Fixed packing absorber.

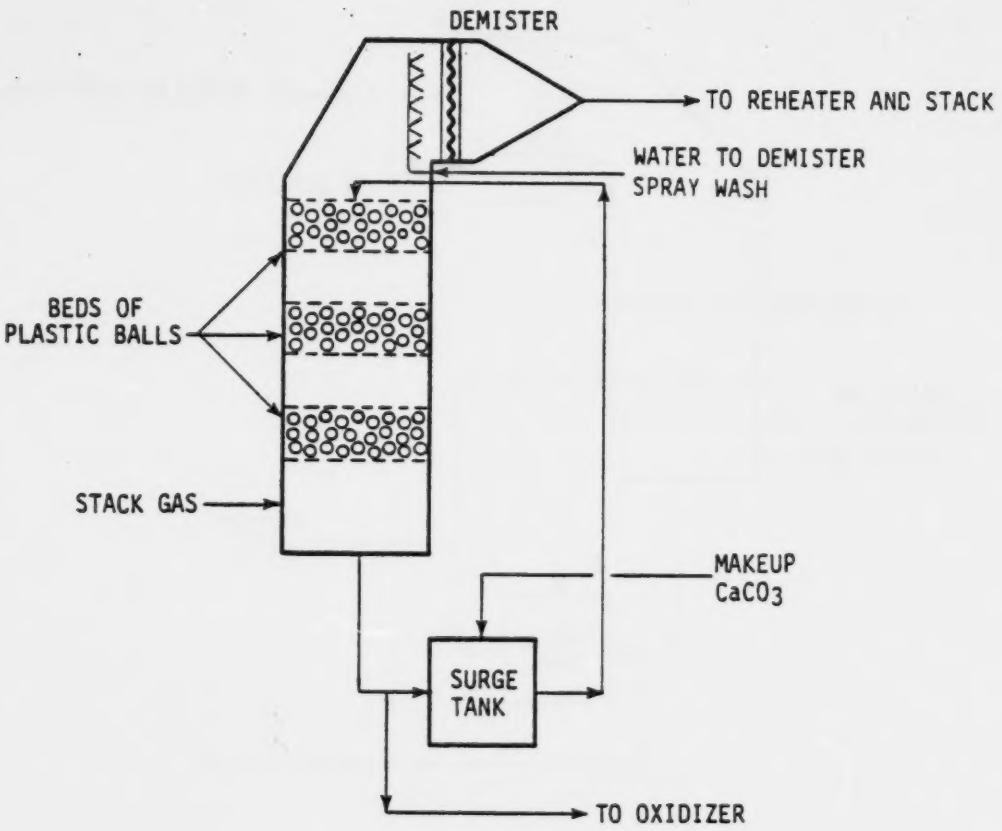

Figure 3. Mobile bed scrubber.

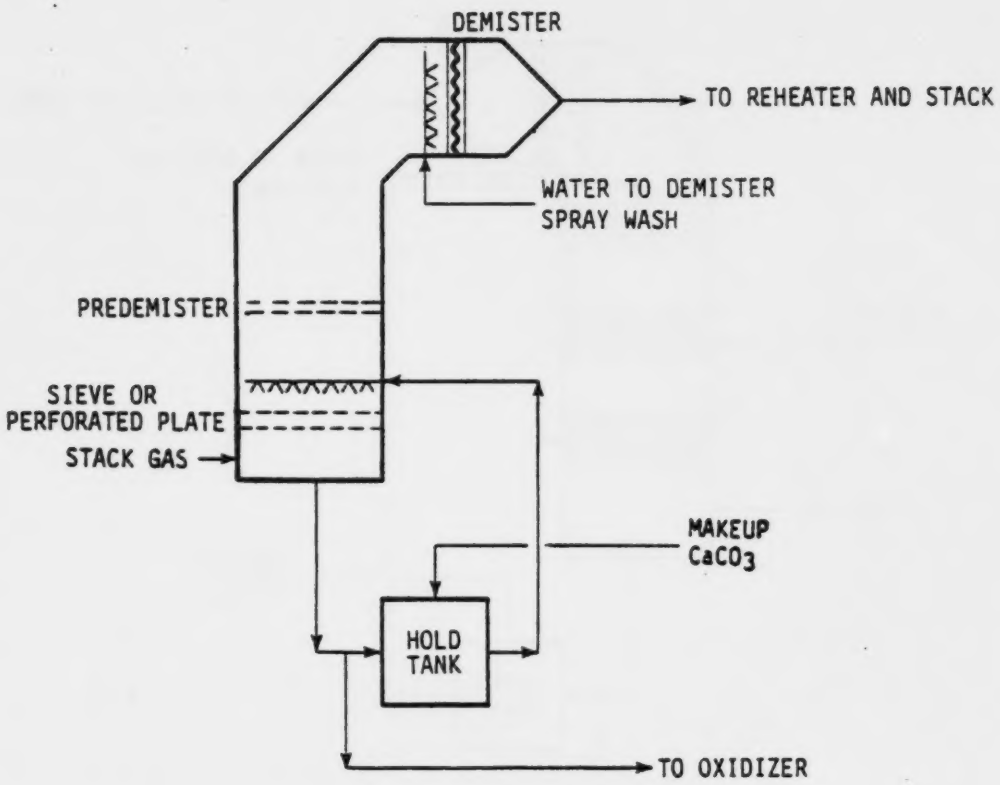

Figure 4. Sieve or perforated tray absorber.

is operated with a dilute slurry at a high L/G ratio to prevent scaling. The by-product contains a considerable number of impurities.

2.2.4 Demister

A demister is required downstream from the absorber to remove entrained water droplets, thereby decreasing downstream equipment corrosion or scaling. Additional reheater energy is required to evaporate any droplets. The droplets are large enough to be removed by a simple change in gas direction. Cyclonic or Z-type vane designs are adequate and can be placed in series to provide additional capacity. Spray washes are installed to reduce the scaling and corrosion to which demisters are subject. Stainless steel and fiberglass-reinforced polyester demisters are more resistant to corrosion. Although demisters can be installed in the horizontal, vertical, or inclined position, the vertical position is most popular in Japan. (Figures 1 though 4 show the demister in the vertical position.)

2.2.5 Reheater

Plume dispersion is generally maintained by heating the stack gas to increase its buoyancy. The extra dispersion makes it easier to meet ambient SO_2 and NO_x standards and also decreases corrosion of downstream equipment and ductwork. Reheat can be accomplished by one of the following

methods: installing a gas or oil burner exhausting directly into the stack, installing steam coils to heat flue gas, injecting air heated by a steam coil into the stack, or by passing some flue gas around the scrubber into the stack. The Japanese systems generally utilize the first option. In-line heat exchangers have a lower capital cost, but are subject to scaling and corrosion and higher maintenance costs.

2.2.6 Receiving and Crushing

To prepare the slurry, limestone is crushed and milled in a ball mill to about a 325-mesh size and mixed with water. The slurry, which is 3 to 10 percent solids, is generally mixed with scrubber liquid effluent in a hold tank.

2.2.7 Gypsum Production

The final step in the system involves oxidation of the calcium sulfite in the slurry to calcium sulfate or gypsum. Because of the high efficiency and reliability of the device, the Mitsubishi-JECCO, Babcock-Hitachi, and Chubu-MKK processes use a rotary atomizer invented by JECCO. Different types of oxidizers have been developed for other processes. A low pH (3.5 to 4.0) is desirable for oxidation of calcium sulfite slurry to the sulfate. This is attained by controlling pH by adding sulfuric acid to the slurry.

Mitsui Miike has developed an alternate scheme for oxidizing the sulfur to gypsum. A soluble metallic catalyst is added to the recirculating slurry. The catalyst prevents the formation of calcium sulfate coating on calcium sulfite and calcium carbonate crystals, thereby allowing them to maintain an exposed reactive surface. This promotes the reaction between $CaCO_3$ and SO_2 and the oxidation of the sulfite into sulfates. The pH of the slurry is reduced to promote oxidation of sulfite to sulfate by contacting the slurry with a portion of the flue gas (5 to 10 percent). The slurry then is mixed with air to oxidize the sulfite to sulfate. The catalyst is washed from the gypsum and precipitated in the form of hydroxide by raising the pH.

The gypsum by-product of this system is ideal for use in wallboard or cement. Although the crystals formed are not very long, they are quite thick, which is an important factor in the strength of the wallboard made. As long as impurities in the gypsum are kept below critical concentrations, they have no ill effects on the wallboard produced. Chloride content of the gypsum can be as high as 0.5 percent. Fly ash, although imparting a brown color to the wallboard, sometimes has no adverse effect with concentrations as high as 5 percent. Gypsum used in cement manufacturing can tolerate higher concentrations of both chloride and fly ash without affecting product quality.

The gypsum slurry from the oxidizer is pumped first to a thickener, then to a centrifuge to reduce free water content.

2.2.8 Wastewater

Supernatant water from the thickener and the centrifuge is largely returned to the system except for a purge stream that is taken off to prevent chloride ion concentration buildup in the system. Water returned to the system is used to make up new limestone slurry, spray wash for demisters, or gas-precooler spray. Chloride ions accumulate in the scrubber system, especially when coal is the boiler fuel. Chloride attacks both steel and stainless steel.

2.3 OPERATING PARAMETERS

2.3.1 Chemical Parameters

Limestone is added to Japanese scrubber systems at a rate 0.95 to 1.2 times the stoichiometric requirement. In contrast, it is added to U.S. limestone/sludge systems at a rate 1.1 to 1.7 times the stoichiometric requirement. The pH of various scrubber systems ranges from 5 to 9. Each manufacturer controls the pH to a different level, but all fall within this range. Systems designed to control pH must rapidly adjust pH back to the control value to avoid reduced efficiency or scaling. This control is especially critical on boilers that frequently change loads or have varying fuel

sulfur contents. The pH of fresh slurry is controlled in the range from 5.0 to 6.7, whereas the pH of slurry in the oxidizing tower is controlled to 3.5 to 4.0. The importance of a low pH can be seen in Figure 5, which shows the relationship between solid composition after oxidation and the pH of the slurry entering the oxidation tower.

2.3.2 Physical Parameters

The primary scrubber in the system can be a particulate scrubber or merely a gas cooler and humidifier. In representative systems in Japan, the L/G ratio is 2 to 10 liters/Nm^3; the throat velocity of the scrubbers is 2 to 17 m/s, and the pressure drop across the primary scrubber is 600 to 2300 Pa.

The second scrubber is the main SO_2 removal device. Its L/G ratio is 7 to 15 liters/Nm^3, the flue gas velocity is 3 to 4 m/s, and the pressure drop across the scrubber is 343 to 4950 Pa.

Flue gas velocities in vertical demisters average around 6 m/s, whereas the optimum flue gas velocity in horizontal demisters is 2.5 m/s. Higher velocity increases the water removal rate, but it also increases the re-entrainment of water before it can leave the demister. Pressure drop across the demister ranges from 100 to 600 Pa.

Flue gas reheat temperatures range from 38° to 84°C at representative boilers in Japan. This requires an energy

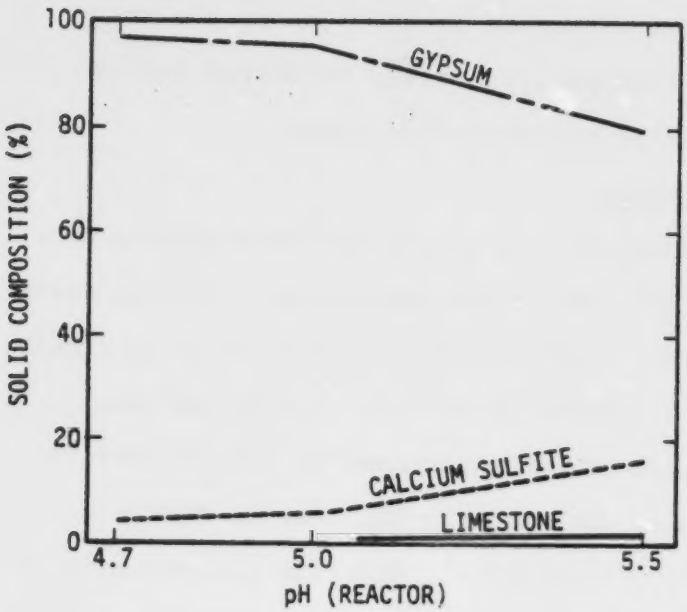

Figure 5. Relationship of slurry pH in reactor to solid composition after oxidation.

expenditure of approximately 1000 J/kg of flue gas/°C of reheat. Pressure drop across the reheater is 25 to 65 Pa.

Typical thickeners or clarifiers can be anywhere from 10 to 40 m in diameter. The size of the centrifuges ranges from 1900 to 11,000 kg/h, and the combined capacity of multiple units from 11,000 to 45,000 kg/h.

3.0 CURRENT STATUS, ASSESSMENT, AND PLANS

The limestone gypsum process, currently the most widely used FGD system in Japan, achieves 90 percent SO_2 control at stoichiometries of 0.9 to 1.2 and L/G's of 7 to 15 liters/Nm^3; it has almost 100 percent availability. Most scaling and plugging problems were solved by careful design and the application of advanced-process control devices to keep the system operating within narrow limits. The quality of the gypsum by-product is similar to that of lime scrubber systems, and limestone is about one-fourth as expensive as lime. As a result, in the last 2 years nearly all new FGD systems in Japan have utilized limestone rather than lime.

New orders for limestone/gypsum FGD systems and other FGD systems are decreasing in Japan for several reasons. The ambient SO_2 standards have nearly been attained, fuel desulfurization techniques have again become cost-competitive with FGD systems, and the gypsum supply is becoming excessive. If this trend continues, the market price of gypsum will drop.

The limestone/gypsum process is a proven system applicable to any area with a gypsum market, a limestone supply, and sufficient space. Gypsum can also be used as landfill and makes an acceptable construction base. Stringent solid waste or water regulations could complicate the use of a gypsum landfill. The system has provided 90 percent or better SO_2 control with 95 percent or better availability on oil and coal-fired boilers with fuel-sulfur contents as high as 2.5 percent. Land requirements for equipment are minimal except for raw material and product storage areas. Limestone requirements are high, and the system should be located near the source of limestone; otherwise, transportation costs become a major factor. Even though capital costs are relatively low, operating labor and maintenance costs are high, generally making it unacceptable to very small systems. New uses for gypsum are being investigated, and the market for gypsum may improve.

Table 1 summarizes the status of surveyed limestone/gypsum systems. The ranges shown for collection efficiency and availability refer only to the surveyed systems, but the rest of the information on the table refers to all limestone/gypsum systems operating in December 1977. Table 2 presents important characteristics of each surveyed facility. More detailed information can be found in the Appendix A.

Table 1. SUMMARY OF STATUS OF LIMESTONE/GYPSUM SYSTEMS INSTALLED ON COMBUSTION SOURCES

All Systems	
Total number of systems in operation by Dec. 77	33
Total number of systems built	33
Total number systems surveyed	6
Year first limestone/gypsum FGD system was placed in commercial service	1973
Number of utilities using limestone/gypsum process	23
Total MW of these facilities	5511
Number of industrial combustion systems using limestone/gypsum process	10
Surveyed Systems	
Range of average SO_2 removal efficiencies, %	90-96
Range of fly ash removal efficiency of FGD, %	75-97
Range of average availability factors[a], %	97-100

[a] See Appendix B for availability calculation factor.

Table 2. STATUS OF SURVEYED FGD INSTALLATIONS - LIMESTONE/GYPSUM PROCESS.

Name of plant	Location	Size, MW	Fuel type	Characteristics		Flue gas treated		Year FGD system started	SO_2 removal efficiency, %	Disposition of end products	Energy required[a] %	Avg. availability, %
				S, %	Heat value	Nm^3/s	% of total					
Kyushu Elec. Karatsu	Karatsu City, Saga Prefecture	875	Heavy oil C or crude oil	1.0	9500 kcal/liter	203 @ 150°C	50	1976	89.9	All has been sold for wallboard and cement	0.57[b]	100
Electric Pwr Development Company Isogo	Isogo-Ku, Yokohama	265 + 265	Coal	0.6	6200 kcal/kg	250 @ 170°C	at 100	1976	90	Sold for cement	2.94[c]	d
Chugoku Electric, Tamashima	Tamashima, Kurashiki City, Okayama Prefecture	500 + 350	Heavy oil C	2.5	10,300 kcal/kg	411 @ 139°C	100	1975	96	Sold for cement and wallboard	2.07[e]	97.7
Electric Pwr Development Company Takehara	Takehara, Hiroshima Prefecture	250	Coal	2.0	6000 kcal/ g 9700 kcal/liter	237 @ 150°C	100	1977	95	Sold for cement	3.4[f]	d
Electric Pwr Development Company Takasago	Takasago, Hyogo Prefecture	250 + 250	Coal	2.2	6700 kcal/kg	236 @ 145°C	100	1975 1976	93	Sold for cement	1.6[g]	97
Sumitomo Metal Ind., Ltd., Kashima	Kashimacho, Ibaraki Prefecture	Gas from sintering machine ~600 MW	[a]	i	i	556 @ 150°C	100	1976	93	Sold as cement setting retarder	1.3[h]	100

[a] Energy requirement for reheating depends mainly on local conditions, not on FGD system. Totals do not include reheat.

[b] In addition 1.1% reheat required.

[c] In addition 1.99% reheat required.

[d] Availability data not available.

[e] In addition 2.58% reheat required.

[f] In addition 4.48% reheat required.

[g] In addition 4.48% reheat required.

[h] In addition 2.56% reheat required.

[i] Not applicable.

4.0 RECENT TECHNOLOGICAL DEVELOPMENTS AND SOLUTIONS TO PROBLEM AREAS

Scaling, the most significant problem encountered in the limestone/gypsum FGD process, results from formation of crystals of $CaSO_4 \cdot 2\ H_2O$, $CaSO_3 \cdot 1/2\ H_2O$ and $CaCO_3$ on the internal parts of the system. Crystallization of gypsum is enhanced when the O_2/SO_2 ratio of the flue gas is high and oxidation of sulfite to sulfate in the scrubber exceeds 20 percent. This is called saturated-mode operation. Although unsaturated-mode operation is being investigated in the United States and Japan, most systems operate in the saturated mode. To reduce scale, improvements have been made in design, fabrication, and operation. Through pilot plant studies, Mitsubishi Industries determined that scaling can be prevented by shape and arrangement of the grid in the absorber, by adjustment of slurry concentration, pH, and L/G ratio, by addition of gypsum crystal seed to recirculating slurry, and by thorough mixing of limestone in the circulating slurry.

Magnesium ion has been found to improve performance in lime and limestone systems.* Magnesium addition helps

* Refer to Status Report on the Limestone/Sludge Process prepared as part of the NATO-CCMS study.

increase efficiency and reduce scaling by reacting with sulfite and bisulfite in solution and increasing SO_2 absorption. The gypsum crystal does not grow as well in this case, and contains about 0.5 percent magnesium sulfate, but it is still useful as a setting retarder in cement.

To decrease chloride corrosion, Kobe Steel has used titanium and pumice-stone lining to fabricate the hot zone of the primary gas cooler.

5.0 COST

Comparing the economics of systems in various countries becomes a complex task because economic factors differ between them. Costs of labor, raw materials, utilities, taxes, interest rates, and depreciation vary greatly and change from year to year.

Inflation rises at a different rate in each country, causing the relative value of money to change continually. Depreciation of fixed costs occurs over seven years in Japan, in contrast to 15 years in the United States. To complicate the matter even further, FGD systems are constructed differently in different countries. Some Japanese systems have extensive pH controls, convert all the sludge to gypsum, and sometimes include spare scrubbers and pumps. This makes the comparison of costs difficult, even when plants are in the same country.

All costs submitted in the questionnaire were assumed to apply to the date of plant start-up unless otherwise indicated. Plant start-up date and length of construction time were generally reported. The dollar cost at initiation of plant construction was converted to January 1976 dollars, using the Chemical Engineering plant cost index (1957-59 =

100, Jan. 1976 = 187.1). These adjusted costs are presented in Table 3. The actual costs are included in the questionnaires in the Appendix.

Cost estimates provided by each company do not include the same things, and the reported data cannot be used to generalize. Electric Power Development Corporation did not provide any costs for its three coal-fired boiler systems. Kyushu Electric, Karatsu City, and Chugoku Electric Tamashima, Kurashiki, provided only a total capital cost. Sumitomo Metal Industries of Kashima, Kashimacho, provided itemized annual costs and the total capital cost for an FGD system installed on a sintering machine.

Table 3. COST DATA OF INDIVIDUAL INSTALLATIONS

FOR THE LIMESTONE/GYPSUM FGD SYSTEM

Company name Plant name Location	Kyushu Elec. Karatsu Karatsu City Japan	EPDC[a] ISOGO Isogo-Ku Japan	EPDC[a] TAKEHARA Takehara Japan	EPDC[a] TAKASAGO Takasago Japan	Chugoku Elec. Tamashima Kurashiki City Japan	Sumitomo Metals Kashima Kashimacho Japan
1. Reported capital cost, $	12,700,000				38,333,000	21,333,000
Year	1973				1975	1976
Cost inflated to 1976[b]	14,400,000				39,100,000	22,220,000
$/kW	32.7[c]				46	37
2. Reported annual costs, $						
Total fixed costs	2,368,600[d]				7,133,625[d]	5,066,000[e]
Fixed charge factor, %	18.65				18.65	22.82
Total variable costs						5,960,000
3. Boiler operating hours	7200	7866	7464	7830	7268	8600
Capacity factor	0.609	0.755	0.768	0.75	0.75	0.95
Generated MWh	4,667,985				5,584,500	4,993,200[f]
4. Reported cost per kWh, mills/kWh						2.21
Fixed cost (boiler operation)					1.28	1.01
Variable costs (actual hours)						1.19
Total cost, mills/kWh						
4000 h						3.64
8000 h						2.21

[a] Electric Power Development Corporation.

[b] Yen are converted to dollars at conversion rate during year construction began and then converted to January 1976 dollars using the Chemical Engineering Plant Index (1957-59 = 100, January 1976 = 187.1). 1 dollar = 300 Yen.

[c] Based on 437.5 MW.

[d] Estimated.

[e] Fixed costs based on 7-year depreciation.

[f] Equivalent not a boiler but a sintering machine.

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APPENDIX A

APPENDIX A. QUESTIONNAIRE DATA ON THE LIMESTONE/GYPSUM FLUE GAS DESULFURIZATION PROCESS

Part A

		MITSUBISHI HEAVY INDUSTRIES Karatsu	BABCOCK HITACHI Tamashima	IHI* Isogo
1.	GENERAL DESCRIPTION			
1.1	Company	Kyushu Electric Company	Chugoku Electric Power	Electric Power Development Co.
1.2	Plant name	Karatsu	Tamashima	Isogo
1.3	Preparer's name and mailing address	Jumpei Ando 1-13, Kasuga Bunkyo-Ku, Tokyo	Jumpei Ando 1-13-27 Kasuga Bunkyo-Ku, Tokyo	Jumpei Ando 1-13-27 Kasuga Bunkyo-Ku, Tokyo
1.4	Principal plant products	Electrical power	Electrical power	Electrical power
	Brief description of area surrounding plant site and factors for choice of FGD system	On reclaimed land facing Karatsu Bay, stringent air regulations required	In Mizushima industrial district facing Seto Inland Sea, stringent regulations applied	SO_2 regulations becoming more stringent; FGD and low-sulfur fuel are required
1.5	Plant location	Karatsu City, Saga Prefecture	Tamashima, Kurashiki City Okayama Prefecture	Isogo-Ku, Yokohama
1.6	STATION CAPACITY			
1.6.1	Total boiler generating capacity MW number of boilers	1175/3	1200/3	530/2
1.6.2	Capacity served by FGD system, MW	875	850	530
	Amount of flue gas treated, Nm^3/h	N.A.	N.A.	1,800,000 (2 units)
	% of boiler flue gas treated by FGD system	50	100	100
	Number of boilers served	2	2	2

Nm^3/h = m^3/h (0°C and 101.325KPa)

N.A. - not available

(continued)

APPENDIX A. QUESTIONNAIRE DATA ON THE LIMESTONE/GYPSUM FLUE GAS DESULFURIZATION PROCESS

Part B

		BABCOCK HITACHI Takehara	MITSUI MIIKE MACHINERY Takasago	FUJIKASUI ENGINEERING CO. Kashima
1.	GENERAL DESCRIPTION			
1.1	Company	Electric Power Development Co.	Electric Power Development Co.	Sumitomo Metal Industries, Ltd.
1.2	Plant name	Takehara	Takasago	Kashima
1.3	Preparer's name and mailing address	Jumpei Ando 1-13 Kasuga Bunkyo-Ku, Tokyo	Jumpei Ando 1-13-27 Kasuga Bunkyo-Ku, Tokyo	Jumpei Ando 1-13-27 Kasuga Bunkyo-Ku, Tokyo
1.4	Principal plant products	Electrical power	Electrical power	Steel
	Brief description of area surrounding plant site and factors for choice of FGD system	On reclaimed land facing Seto Inland Sea, boiler No. 1 has FGD boiler	N.A.	In Kashima industrial district facing the Pacific Ocean, stringent regulations applied
1.5	Plant location	Takehara Hiroshima Prefecture	Takasago Hyogo Prefecture	Kashimacho, Ibaraki Prefecture
1.6	STATION CAPACITY			
1.6.1	Total boiler generating capacity, MW /number of boilers	600/2	500/2	N.A.
1.6.2	Capacity served by FGD system, MW	250	500	N.A.
	Amount of flue gas treated, Nm^3/h	N.A.	N.A.	2,000,000
	% of boiler flue gas treated by FGD system	100	100	100
	Number of boilers served	1	2	1 (sintering machine)

(continued)

APPENDIX A (continued) Part A

		MITSUBISHI HEAVY INDUSTRIES Kuratsu	BABCOCK HITACHI Tamashima	IHI* Isogo
1.7	Type of FGD system	Limestone/gypsum process	Limestone/gypsum process	Limestone/gypsum process
1.8	Number of scrubber trains in parallel	1	4	1
1.9	FGD system installed on new or existing boiler	Existing	Existing	Existing
1.10	STATUS OF FGD SYSTEM operational or under construction, date started	Operational, July 1976	Operational, 1975	Operational No. 1 March 1976, No. 2 May 1976
2.	BOILER DATA			
2.1	Boiler identification number	No. 3	No. 3	No. 1, No. 2
2.2	Maximum continuous heat input, MW	N.A.	N.A.	N.A.
2.3	Max. cont. net generating capacity, MW	N.A.	N.A.	N.A.
2.4	Flue gas flow rate, Nm^3/h	N.A.	1,480,000	900,000
	temperature at induced draft fan, °C	N.A.	139	170
2.5	Boiler manufacturer	Mitsubishi Heavy Industries	Babcock Hitachi	IHI
2.5.1	Fuel type	Heavy oil C or crude oil	Heavy oil	Coal (low-sulfur)
2.5.2	Firing configuration	Corner firing	Opposite firing	Opposite firing
2.6	Year placed in service	1973	1974	No. 1 - 1967 No. 2 - 1969
2.7	Type service	Base load	Base load	Base load
2.8	Stack height, m	180	230	No. 1 - 120 No. 2 - 140
2.8.1	Flue gas exit velocity, m/s	32	36.4	34.4
2.9	Average boiler operation, h/yr	7200/1976	7268/1976	7866/1976
2.10	Average boiler capacity factor	0.609	0.75	0.755

(continued)

APPENDIX A (continued) Part B

		BABCOCK HITACHI Takehara	MITSUI MIIKE MACHINERY Takasago	FUJIKASUI ENGINEERING CO. Kashima
1.7	TYPE OF FGD SYSTEM	Limestone/gypsum	Limestone/gypsum	Limestone/gypsum
1.8	Number of scrubber trains in parallel	2 (no stand-by)	1	2 (no stand-by)
1.9	FGD system installed on new or existing boiler	Existing	Existing	New sintering machine
1.10	STATUS OF FGD SYSTEM operational or under construction, date started	Operational, Feb. 1977	Operational, No. 1 Feb. 1975 No. 2 Mar. 1976	Operational, July 1976
2.	BOILER DATA			
2.1	Boiler identification number	No. 1	No. 1, No. 2	No. 3 sintering machine
2.2	Maximum continuous heat input, MW	N.A.	N.A.	None
2.3	Max. cont. net generating capacity, MW	250	500	909,091 kg/h sintered ore 600 equivalent
2.4	Flue gas flow rate, Nm^3/h	852,000	840,000	2,000,000
	temperature at induced draft fan, C°	150	144	N.A.
2.5	Boiler manufacturer	Babcock Hitachi	Mitsubishi Heavy Industries	None
2.5.1	Fuel type	Coal	Coal	Coke
2.5.2	Firing configuration	Opposite firing	Corner firing	None
2.6	Year placed in service	1967	No. 1, 1968 No. 2, 1969	1976
2.7	Type service	Base load	Base load	None
2.8.	Stack height, m	200	180	200
2.8.1	Flue gas exit velocity, m/s	35.2	32.6	19
2.9	Average boiler operation, h/yr	7464/1976	7830/1976	8600
2.10	Average boiler capacity factor	0.768	0.752	N.A.

(continued)

APPENDIX A (continued) Part A

		MITSUBISHI HEAVY INDUSTRIES Kuraten	BABCOCK HITACHI Tamashima	IHI* Isogo
2.11	COAL COMPOSITION	None	None	
2.11.1	Lower heating value, kJ/kg			23,740
2.11.2	Sulfur content, %			0.6
2.11.3	Ash content, %			16.0
2.11.4	Chloride content, %			N.A.
2.11.5	Moisture, %			7.0
2.12	OIL COMPOSITION			
2.12.1	Grade/heating value, kJ/kg	N.A.	N.A.	N.A.
2.12.2	Sulfur content, %	1.0 (average)	2.5	1.0, Emergency 0.3
2.12.3	Ash content, %	0.01	N.A.	N.A.
2.12.4	Chloride content, %	N.A.	N.A.	N.A.
2.13	PARTICULATE REMOVAL EQUIPMENT NOT PART OF FGD SYSTEM			
2.13.1	Type	Electrostatic precipitator	Electrostatic precipitator	Electrostatic precipitator
2.13.2	Manufacturer	N.A.	Hitachi Ltd.	N.A.
2.13.3	Efficiency, % removal	N.A.	82 (design)	N.A.
2.13.4	Emission rate, mg/Nm^3	N.A.	N.A.	N.A.

(continued)

APPENDIX A (continued) Part B

		BABCOCK HITACHI Takehara	MITSUI MIIKE MACHINERY Takasago	FUJIKASUI ENGINEERING CO. Kashima
2.11	COAL COMPOSITION			None
2.11.1	Lower heating value, kj/kg	25,120	25,960	
2.12.2	Sulfur content, %	2.0	2.2	
2.11.3	Ash content, %	23.0	22.0	
2.11.4	Chloride content, %	N.A.	N.A.	
2.11.5	Moisture, %	7.0	7.0	
2.12	OIL COMPOSITION	Heavy oil C	Heavy oil C	None
2.12.1	Grade/heating value (kcal/ℓ)	9800	9800	
2.12.2	Sulfur content, %	3.0, Emergency 0.4	3.0, Emergency 0.3	
2.12.3	Ash content, %	N.A.	N.A.	
2.12.4	Chloride content, %	N.A.	N.A.	
2.13	PARTICULATE REMOVAL EQUIPMENT NOT PART OF FGD SYSTEM			
2.13.1	Type	Electrostatic precipitator	Electrostatic precipitator	Electrostatic precipitator
2.13.2	Manufacturer	N.A.	N.A.	Sumitomo Heavy Industries
2.13.3	Efficiency, % removal	N.A.	N.A.	95
2.13.4	Emission rate, mg/Nm^3	N.A.	N.A.	N.A.

(continued)

APPENDIX A (continued) Part A

		MITSUBISHI HEAVY INDUSTRIES Karatsu	BABCOCK HITACHI Tamashima	IHI* Isogo
3.	EMISSION REGULATIONS			
3.1	ATMOSPHERIC EMISSIONS			
3.1.1	SO_2, Nm^3/h	447	82	48
3.1.2	Particulate, mg/Nm^3	38	40	50
3.1.3	NO_x, ppm	200	180	N.A.
3.1.4	Other	N.A.	N.A.	N.A.
3.1.5	Legal basis	Agreement with Karatsu City	National standard	Agreement with Yokohama City
3.2	RESTRICTIONS APPLICABLE TO LIQUID OR SOLID WASTES, LEGAL BASIS	pH 5.8-8.6 COD below 20 ppm SS below 30 ppm oil below 1 ppm Agreement with Karatsu City	pH 5.8-8.6 COD below 15 mg/ℓ SS below 40 mg/ℓ oil below 3 mg/ℓ Wastewater agreement with Karashiki City	N.A.
4.	FGD SYSTEM INFORMATION			
4.1	Process name	Limestone/gypsum process	Limestone/gypsum	Limestone/gypsum
4.1.1	Supplier or design company	Mitsubishi Heavy Industries	Babcock Hitachi	IHI - Chemico
4.1.2	WHY WAS THIS SYSTEM CHOSEN?	Reliability of operation and non-toxicity of by-product gypsum	Pilot plant tests carried out by Chugoku Electric; jointly, Babcock was successful	N.A.
4.1.3	PROCESS DESCRIPTION	Appendix Figure A	Appendix Figure B and C	Appendix Figure D

(continued)

APPENDIX A (continued) Part B

		BABCOCK HITACHI Takehara	MITSUI MIIKE MACHINERY Takasago	FUJIKASUI ENGINEERING CO. Kashima
3.	EMISSION REGULATIONS			
3.1	ATMOSPHERIC EMISSIONS			
3.1.1	SO_2, Nm^3/h	456/boiler No. 1	200/boiler	976 (from entire works)
3.1.2	Particulate, mg/Nm^3	100	50	50
3.1.3	NO_x, ppm	420	300	N.A.
3.1.4	Other	N.A.	N.A.	N.A.
3.1.5	Legal basis	Agreement with Takehara City	Agreement with Takasago City	Iberaki Perfecture
3.2	RESTRICTIONS APPLICABLE TO LIQUID OR SOLID WASTES, LEGAL BASIS	N.A.	N.A.	N.A.
4.	FGD SYSTEM INFORMATION			
4.1	Process name	Babcock Hitachi Limestone/gypsum process	Mitsui-Chemico Limestone/gypsum process	Moretana line/limestone gypsum process
4.1.1	Supplier or design company	Babcock Hitachi	Mitsui Miike Machinery	Fugikasui Engineering Co.
4.1.2	WHY WAS THIS SYSTEM CHOSEN?	Limestone is used to by-produce salable gypsum. Stable operation with high SO_2 removal efficiency	Limestone is cheap and produces salable gypsum. Successful operation of Omuta plant; Mitsui aluminum using Chemico scrubber for flue gas from scrubber	Process developed jointly by Fuzikasui and Sumitomo Metal Industries
4.1.3	PROCESS DESCRIPTION	Appendix Figure E	Appendix Figure F	Appendix Figures G, H, and I

(continued)

APPENDIX A (continued) Part A

		MITSUBISHI HEAVY INDUSTRIES Kuratsu	BABCOCK HITACHI Tamashima	IHI* Isogo
4.2	SO_2 SCRUBBING AGENT			
4.2.1	Name	Limestone	Limestone	Limestone
4.2.2	Chemical composition	N.A.	$CaCO_3$ MgO	$CaCO_3$
	Components, % by weight	N.A.	$CaCO_3$, over 98 MgO, below 0.6	$CaCO_3$, over 98
4.2.3	Stoichiometric requirement	N.A.	N.A.	1.0-1.05
4.2.4	Addition rate, kg/h	1873 at MCR	N.A.	2000 (or more)
4.2.5	Particle size, mm	Below 0.044 (avg.)	95% below 0.044	Below 0.044
4.3	REGENERATION AGENT	None	None	None
4.3.1	Name			
4.3.2	Composition			
4.3.3	Stoichiometric requirement			
4.3.4	Addition rate			
4.3.5	Particle size			
4.4	SALABLE PRODUCT			
4.4.1	Name	Gypsum	Gypsum	Gypsum
4.4.2	Chemical composition Components, % by weight	N.A.	$CaSO_4 \cdot 2H_2O$ Moisture, below 10%	$CaSO_4 \cdot 2H_2O$, 75-85 Fly ash, 10-20 Moisture, 15
4.4.3	Amount generated/year, Mg/yr	14,000	84,000	41,000
4.4.4	Sales potential	All has been sold for wallboard	Sold for cement and wallboard	Sold for cement

(continued)

APPENDIX A (continued) Part B

		BABCOCK HITACHI Takehara	MITSUI MIIKE MACHINERY Takasago	FUJIKASUI ENGINEERING CO. Kashima
4.2	SO_2 SCRUBBING AGENT			
4.2.1	Name	Limestone	Limestone	Limestone (occasionally lime)
4.2.2	Chemical composition	$CaCO_3$	$CaCO_3$	$CaCO_3$ $Ca(OH)_2$
	Components, % by weight	$CaCO_3$, about 98	$CaCO_3$, about 98	$CaCO_3$, about 99 $Ca(OH)_2$, about 94
4.2.3	Stoichiometric requirement	1.05 mole $CaCO_3$/mole SO_2	1.0	1.0
4.2.4	Addition rate, ton/h	5660 @ MCR	6600 @ MCR	N.A.
4.2.5	Particle size, mm	95% below 0.044	95% below 0.044	$CaCO_3$ below 0.044 $Ca(OH)_2$ below 0.080
4.3	REGENERATION AGENT	None	None	None
4.3.1	Name			
4.3.2	Composition			
4.3.3	Stoichiometric requirement			
4.3.4	Addition rate			
4.3.5	Particle size			
4.4	SALABLE PRODUCT			
4.4.1	Name	Gypsum	Gypsum	Gypsum
4.4.2	Chemical composition Components, % by weight	$CaSO_4 \cdot 2H_2O$, over 95 H_2O, about 10	$CaSO_4 \cdot 2H_2O$, over 95 Fly ash, below 1 Moisture, about 10	$CaSO_4 \cdot 2H_2O$, about 90 Moisture, below 10
4.4.3	Amount generated/year, Mg/yr	70,000	118,000 (approximate)	20,000
4.4.4	Sales potential	For cement	Salable for cement	Mainly for cement (setting retarder)

(continued)

APPENDIX A (continued) Part A

		MITSUBISHI HEAVY INDUSTRIES Karatsu	BABCOCK HITACHI Tamashima	IHI[a] Isogo
4.4.5	BY-PRODUCT RECOVERY PROCESS	N.A.		
	Name		N.A.	IHI gypsum recovery process
	Vendor		N.A.	IHI
	Process description		Oxidation and filtration	Oxidation of $CaSO_4$ then centrifuge
4.4a	Intermediate product composition	None	None	None
4.5	BY-PRODUCT NO. 2	None	None	None
4.6	WASTE STREAMS	N.A.		N.A.
4.6.1	Type of waste		Wastewater	
	% water		N.A.	
4.6.2	Amount generated in one hour at full load, m^3/h		4	
4.6.3	Disposal method		Wastewater treatment to meet regulations	
4.6.4	Disposal site and distance from plant, km		N.A.	
4.6.5	Potential effects on environment from sludge disposal		N.A.	
4.7	SLUDGE FIXATION PROCESS	None	None	None

(continued)

APPENDIX A (continued) Part B

		BABCOCK HITACHI Takehara	MITSUI MIIKE MACHINERY Takasago	FUJIKASUI ENGINEERING CO. Kashima
4.4.5	BY-PRODUCT RECOVERY PROCESS			
	Name	N.A.	N.A.	N.A.
	Vendor	N.A.	N.A.	Mitsui Miike Machinery
	Process description	Air oxidation and centrifuge	N.A.	N.A.
4.4a	Intermediate product composition			
4.5	BY-PRODUCT NO. 2	None	None	None
4.6	WASTE STREAMS			
4.6.1	Type of waste	N.A.	N.A.	N.A.
	% water	N.A.	N.A.	N.A.
4.6.2	Amount generated in one hour at full load, kg/h	13,600	13,600	27,200
4.6.3	Disposal method	N.A.	N.A.	Neutralization and setting
4.6.4	Disposal site and distance from plant, km	N.A.	N.A.	N.A.
4.6.5	Potential effects on environment from sludge disposal	N.A.	N.A.	N.A.
4.7	SLUDGE FIXATION PROCESS	None	None	None

(continued)

APPENDIX A (continued) Part A

		MITSUBISHI HEAVY INDUSTRIES Kuratsu	BABCOCK HITACHI Tamashima	IHI* Isogo
4.8	FGD EQUIPMENT DATA			
4.8.1	FIRST SCRUBBER			
4.8.1.1	Type	Spray	Venturi	Venturi
4.8.1.2	L/G ratio, ℓ/Nm^3	2	10	7.8
4.8.1.3	Gas velocity through absorber or scrubber, m/s	2.0	16.4	3.
4.8.1.4	Absorbent (adsorbent) flow, m^3/h	N.A.	N.A.	N.A.
4.8.1.5	Gas flow entering scrubber, Nm^3/h	730,000	1,480,000	900,000
4.8.1.6	Gas temperature, °C	150	139	170
4.8.1.7	Gas composition			
	SO_2 in + out, ppm	530 + 525	1460 +	500 + 160
	% removal	1	N.A.	N.A.
	Particulate in + out, mg/Nm^3	24 + 7	40 + N.A.	1500 + 50
	% removal	71	N.A.	N.A.
	NO_x in + out, ppm	N.A.	180	N.A.
	CO_2 in + out, ppm	11.2% + 11.7%	N.A.	N.A.
	Other in + out	N.A.	N.A.	N.A.
4.8.1.8	Material of construction	Mild steel(ss)	Mild steel	Carbon steel
4.8.1.9	Type of lining	Plastic above, stone below	Resin	Flake lining
4.8.1.10	Adsorbent and sand losses	None	None	None
4.8.1.11	Number of stages	N.A.	N.A.	1
4.8.1.12	Packing type and composition	N.A.	N.A.	N.A.

(continued)

APPENDIX A (continued) Part B

	BABCOCK HITACHI Tokohara	MITSUI MIIKE MACHINERY Tokosago	FUJIKASUI ENGINEERING CO. Kashima
4.0 FLU EQUIPMENT DATA			
4.0.1 FIRST SCRUBBER			
4.0.1.1 Type	Venturi	Venturi	Perforated plate tower (Moretana)
4.0.1.2 L/G* ratio (ℓ/m^3)	2.2	5.3 ∿ 6.6	7.0
4.0.1.3 Gas velocity through absorber or scrubber, m/s	N.A.	N.A.	4.5
4.0.1.4 Absorbent (adsorbent) flow, m^3/h	N.A.	N.A.	N.A.
* Liquid-to-gas ratio			
4.0.1.5 Gas flow entering scrubber, m^3/h	852,000	840,000 (per unit)	1,000,000 (per scrubber)
4.0.1.6 Gas temperature, °C	150	144	150
4.0.1.7 Gas composition			
SO_2 in • out, ppm	1710 • 1210	1500 • N/A	400-600 • 360-540
% removal	30	N.A.	10
Particulate in • out, mg/Nm^3	600 • 50	100 • 74	100-200 • 20
% removal	92	26	80-90
NO_x in • out, ppm	N.A.	N.A.	150-250 • 150-250
CO_2 in • out, ppm	N.A.	N.A.	6-7% • 6-7%
Other in • out	N.A.	N.A.	N.A.
4.0.1.8 Material of construction	Steel	N.A.	316 L and resin liner
4.0.1.9 Type of lining	N.A.	Flake lining	Vinyl ester
4.0.1.10 Absorbent and sand losses	None	None	None
4.0.1.11 Number of stages	2	1	6
4.0.1.12 Packing type and composition	N.A.	N.A.	N.A.

(continued)

APPENDIX A (continued) Part A

		MITSUBISHI HEAVY INDUSTRIES Kuratsu	BABCOCK HITACHI Tamashima	IHI* Isogo
4.8.2	SECOND SCRUBBER			
4.8.2.1	Type	Grid packed	Perforated plate tower	Venturi
4.8.2.2	L/G ratio, l/m^3	12	10	7.8
4.8.2.3	Gas velocity through absorber or scrubber, m/s	3	N.A.	3
4.8.2.4	Absorbent (adsorbent) flow, tons/h	N.A.	N.A.	2.0 $CaCO_3$
4.8.2.5	Gas flow entering scrubber, Nm^3/h	730,000	1,500,000	999,000
4.8.2.6	Gas temperature, °C	56	55	54.8
4.8.2.7	Gas composition			
	SO_2 in + out, ppm	525 + 53	1450 + 58	160 + 50
	% removal	89.9	96	90
	Particulate in + out, mg/Nm^3	7 + 6	N.A.	N.A. + 50
	% removal	N.A.	N.A.	N.A.
	NO_x in + out, ppm	N.A.	N.A.	N.A.
	% removal	N.A.	N.A.	N.A.
	CO_2	11.7% + 11.7%	N.A.	N.A.
	Other	N.A.	N.A.	N.A.
4.8.2.8	Material of construction	Mild steel	Mild steel	Carbon steel
4.8.2.9	Type of lining	Plastic	Resin	Flake lining
4.8.2.10	Number of stages	6 (grid stages)	5	1
4.8.2.11	Packing type and composition	Plastic grids	N.A.	N.A.

(continued)

APPENDIX A (continued) Part B

	BABCOCK HITACHI Takahara	MITSUI MIIKE MACHINERY Takasago	FUJIKASUI ENGINEERING CO. Kashima
4.8.2 SECOND SCRUBBER			
4.8.2.1 Type	Perforated plate tower	Venturi	(Moretana) special perforated plate tower
4.8.2.2 L/G ratio (ℓ/Nm^3)	7	6	8
4.8.2.3 Gas velocity through absorber of scrubber, m/s	N.A.	N.A.	4.4
4.8.2.4 Absorbent (adsorbent) flow, m^3/h	N.A.	N.A.	N.A.
4.8.2.5 Gas flow entering scrubber, Nm^3/h	921,000	N.A.	1,000,000 (per scrubber)
4.8.2.6 Gas temperature, °C	52	52	55
4.8.2.7 Gas composition			
SO_2 in + out, ppm	1210 + 100	N.A. + 100	360-540 + 30
% removal	92	N.A.	92-94
Particulate in + out, mg/Nm^3	N.A. + 50	74 + 50	20 + 20
% removal	N.A.	32	N.A.
NO_x in + out, ppm	N.A.	N.A.	150-250 + 150-250
% removal	N.A.	N.A.	N.A.
CO_2	N.A.	N.A.	6-7% + 6-7%
Other	N.A.	N.A.	O_2 15-18% + 15-18%
4.8.2.8 Material of construction	Steel	N.A.	316 L
4.8.2.9 Type of lining	Flake lining	Flake lining	None
4.8.2.10 Number of stages	2	1	4 plates
4.8.2.11 Packing type and composition	Perforated plates	N.A.	N.A.

(continued)

		MITSUBISHI HEAVY INDUSTRIES Kuratsu	BABCOCK HITACHI Tamashima	IHI* Isogo
4.8.3	CLEAR WATER TRAY		None	
4.8.3.1	Type	Rectangular		Not installed
4.8.3.2	L/G ratio, ℓ/Nm^3	N.A.		N.A.
4.8.3.3	Source of water	Industrial water		N.A.
4.8.4	DEMISTER			
4.8.4.1	Type	Chevron	Pipe type	Chevron
4.8.4.2	Number of passes (stages)	2	2	4
4.8.4.3	Material of construction	Mild steel plastic lined	FRP	Plastic
4.8.4.4	Method of cleaning	Water spray	Water wash	Water wash
4.8.4.5	Flow rate during cleaninge, kg/h		22000/tower	
4.8.4.6	Frequency and duration of routine cleaning	45 second spray every 7 minutes	5 minutes every 80 minutes	5 minutes hourly
4.8.5	REHEATER			
4.8.5.1	Type	Afterburner	Afterburner	Afterburner
4.8.5.2	Heat load	24.7 10^3 kcal/h	55.5 kcal/h	2600 kg/h (C-oil)
4.8.5.3	Heat transfer surface area, m^2	89.5	None	None
4.8.5.4	Temperature of gas in, °C out, °C	56 140	55 139	54 120
4.8.5.5	Reheater materials of construction	Refractories	Steel and refractory	Refractories

(continued)

APPENDIX A (continued) Part B

	BABCOCK HITACHI Takehara	MITSUI MIIKE MACHINERY Takasago	FUJIKASUI ENGINEERING CO. Kashima
4.8.3 CLEAR WATER TRAY	None	None	None
4.8.3.1 Type			
4.8.3.2 L/G ratio, ℓ/Nm^3			
4.8.3.3 Source of water			
4.8.4 DEMISTER			
4.8.4.1 Type	Pipe type	Chevron	Impingement type
4.8.4.2 Number of passes (stages)	4	4	2
4.8.4.3 Material of construction	Plastic	Polypropylene	Propropylene
4.8.4.4 Method of cleaning	Water spray	Water wash	Water spray
4.8.4.5 Flow rate during cleanings, Nm^3/h	6 x 2 stages	N.A.	N.A.
4.8.4.6 Frequency and duration of routine cleaning	80 minutes per cycle	N.A.	1 minute spray every 15 minutes
4.8.5 REHEATER			
4.8.5.1 Type	After burner	After burner	After burner
4.8.5.2 Heat load	3000 ℓ/h (C-oil)	3000 ℓ/h (C-oil)	1760 kcal/m^3
4.8.5.3 Heat transfer surface area, m^2	None	None	None
4.8.5.4 Temperature of gas in, °C out, °C	53 120	52 120	55 110
4.8.5.5 Reheater materials of construction	Refractories	Refractories	Steel and refractories

(continued)

APPENDIX A (continued) Part A

		MITSUBISHI HEAVY INDUSTRIES Karatsu	BABCOCK HITACHI Tamashima	IHI* Isogo
4.8.6	SCRUBBER TRAIN PRESSURE DROP, mbar			
4.8.6.1	First scrubber	6	22	15
4.8.6.2	Second rubber	3	49	15
4.8.6.3	Clear water tray	N.A.	N.A.	N.A.
4.8.6.4	Demister	6	2	5
4.8.6.5	Reheater	N.A.	6	5 (max.)
4.8.6.6	Ductwork	2	25	20
4.8.6.7	Total FGD system	18	106	69
4.8.6.8	I.D. fan	N.A.	122	78 (design)
4.9	SYSTEM MAKEUP WATER ADDED, m^3/h	30	94.5	80.4/unit
4.9.1	Water added per mole of SO_2 removed, m^3/kg mol	N.A.	N.A.	N.A.
4.9.2	Source of makeup	Industrial water	Industrial water	Industrial water
4.9.3	Where is water added	Cooling tower, mist eliminator	Cooler inlet and absorber outlet	Mist eliminator, 1st and 2nd scrubber
4.10	BYPASS SYSTEM			
4.10.1	Can flue gas be bypassed?	Yes	Yes	Yes
4.10.2	Height of gas discharge when bypassed, m	N.A.	N.A.	N.A.
4.11	SLURRY DATA, pH, % of solids by weight	N.A.	N.A.	N.A.
4.11.1	Fresh slurry to scrubber			
4.11.2	Recirculating slurry			
4.11.3	Waste slurry			

(continued)

APPENDIX A (continued) Part B

		BABCOCK HITACHI Takehara	MITSUI MIIKE MACHINERY Takasago	FUJIKASUI ENGINEERING CO. Kashima
4.8.6	SCRUBBER TRAIN PRESSURE DROP, mbar			
4.8.6.1	First scrubber	23	15	18
4.8.6.3	Clear water tray	None	None	None
4.8.6.4	Demister	1	5	3
4.8.6.5	Reheater	25	N.A.	5
4.8.6.6	Ductwork	32	N.A.	14
4.8.6.7	Total FGD system	N.A.	63	52
4.8.6.8	I.D. fan	N.A.	107	59
4.9	SYSTEM MAKEUP WATER ADDED, kg/h	65,455	47,273/unit	N.A.
4.9.1	Water added per mole of SO_2 removed, m^3/kg mol	N.A.	N.A.	N.A.
4.9.2	Source of makeup water	Industrial water	River water	Industrial water
4.9.3	Where is water added	Prescrubber circulation tank	N.A.	Mostly to prescrubber (cooler)
4.10	BYPASS SYSTEM			
4.10.1	Can flue gas be bypassed?	Yes	Yes	Yes
4.10.2	Height of gas discharge when bypassed, m	N.A.	N.A.	200
4.11	SLURRY DATA, pH, % solids by weight			
4.11.1	Fresh slurry to scrubber	6~7, 20	N.A.	12.0,with $Ca(OH)_2$ 9.0,with $CaCO_3$
4.11.2	Recirculating slurry	5.5~6, 8.5	6.2,5-6	6.7,7-8
4.11.3	Waste slurry	2-4,10	N.A.	5-7,7-8

(continued)

APPENDIX A (continued) Part A

		MITSUBISHI HEAVY INDUSTRIES Karatsu	BABCOCK HITACHI Tamashima	IHI* Isogo
4.12	SPENT SLURRY SYSTEM		N.A.	N.A.
4.12.1	Clarifiers	N.A.		
4.12.1.1	Number			
4.12.1.2	Diameter, m			
4.12.2	Solid separation			
4.12.2.1	Type	Centrifuge, basket type		
4.12.2.2	Cloth area, m^2	None		
4.12.2.3	Capacity (wet cake), Mg/h	N.A.		
4.13	SPACE REQUIRED, EXCLUSIVE OF SLUDGE DISPOSAL AREA, m^2	Appendix Figure K	Appendix Figure B	N.A.
4.14	PERSONNEL, man-hours/yr			
4.14.1	Operating	For both FGD	N.A.	N.A.
4.14.1.1	Specialists	6,240 (approximate)	17,520	N.A.
4.14.1.2	Unskilled	12,480 (approximate)	17,520	N.A.
4.14.2	Maintenance and repair	N.A.	N.A.	N.A.
4.15	ENVIRONMENTAL LOAD			
4.15.1	Wastewater treatment process	Neutralization and precipitation	Filtration, oxidation and neutralization	Neutralization, filtration, and COD removal
4.15.2	Concentrations	ss, 148 mg/ COD, 22 ppm	ss, below 40 ppm COD, below 15 ppm	COD, below 10 ppm ss, below 10 ppm oil, below 1 ppm
4.15.3	Appearance of flue gas discharge - any mist problems?	None	N.A.	None

(continued)

APPENDIX A (continued) Part B

		BABCOCK HITACHI Takahara	MITSUI MIIKE MACHINERY Takasago	FUJIKASUI ENGINEERING CO. Kashima
4.12	SPENT SLURRY SYSTEM			
4.12.1	Clarifiers			
4.12.1.1	Number	1	1	1
4.12.1.2	Diameter, m	14	10	40
4.12.2	Solid separation			
4.12.2.1	Type	9 Centrifuge (bucket type)	Centrifuge (14 bucket type units) (7 per unit)	Centrifuge (6 units) 3 (per unit)
4.12.2.2	Cloth Area, m^2	N.A.	N.A.	N/A
4.12.2.3	Capacity (wet cake), Mg/h	11.4	N.A.	1.5 (per unit)
4.13	SPACE REQUIRED, EXCLUSIVE OF SLUDGE DISPOSAL AREA, m^2	N.A.	N.A.	Appendix Figure G and H
4.14	PERSONNEL man-hours/yr	N.A.		
4.14.1	Operating		N.A.	N.A.
4.14.1.1	Specialists		1095/unit	930
4.14.1.2	Unskilled		1095/unit	15,890
4.14.2	Maintenance and repair		N.A.	600
4.15	ENVIRONMENTAL LOAD			
4.15.1	Wastewater treatment process	Neutralization & Precipitation "COD" removal	Filtration, Oxidation & Neutralization "COD" removal	N.A.
4.15.2	Concentrations, ppm	COD, 15 SS, 15 OIL, 1	COD, 10 SS, 10 OIL, 1	Cl, 1500 SO_4, 2000
4.15.3	Appearance of flue gas discharge - any mist problems?	None	None	Slight plume but no mist problems

(continued)

APPENDIX A (continued) Part A

		MITSUBISHI HEAVY INDUSTRIES Karatsu	BABCOCK HITACHI Tamashima	IHI* Isogo
4.16	FGD SYSTEM OPERATION			
4.16.1	% of boiler load FGD can operate	36-100	30-100	25-100
4.16.2	Lag time, MW/min	20	30	10-14
5.	ACTUAL COSTS FOR TOTAL FGD INSTALLATION, year	N.A.	1975	N.A.
5.1	CAPITAL COSTS, $			
5.1.1	Scrubber	N.A.	N.A.	N.A.
5.1.2	Absorbent/regeneration system	N.A.	N.A.	N.A.
5.1.3	Sludge disposal system	N.A.	N.A.	N.A.
5.1.4	Site improvements	N.A.	N.A.	N.A.
5.1.5	Land, roads, tracks, substation	N.A.	N.A.	N.A.
5.1.6	Engineering costs	N.A.	N.A.	N.A.
5.1.7	Contractor's fee	N.A.	N.A.	N.A.
5.1.8	Interest during construction	N.A.	N.A.	N.A.
	Construction period, mo	N.A.	14	N.A.
5.1.9	License fees	N.A.	N.A.	N.A.
5.1.10	Other	N.A.	N.A.	N.A.
5.1.11	Total, $	12.7 million (3.8 billion ¥)	38.3 million (11.5 billion ¥)	N.A.
	$/kW	50.8	76.6	

(continued)

APPENDIX A (continued) Part B

		BABCOCK HITACHI Takehara	MITSUI MIIKE MACHINERY Takeoego	FUJIKASUI ENGINEERING CO. Koshima
4.16	FGD SYSTEM OPERATION		N.A.	
4.16.1	% of boiler load FGD can operate	25-100		25-100
4.16.2	Lag time	None		0
5.	ACTUAL COSTS FOR TOTAL FGD INSTALLATION, year	N.A.	N.A.	1976
5.1	CAPITAL COSTS, $			
5.1.1	Scrubber			
5.1.2	Absorbent/regeneration system			
5.1.3	Sludge disposal system			
5.1.4	Site improvements			
5.1.5	Land, roads, tracks substation			
5.1.6	Engineering costs			
5.1.7	Contractor's fee			
5.1.8	Interest during construction			
	Construction period, mo			
5.1.9	License fees			
5.1.10	Other			
5.1.11	Total, $			21.3 million (6.4 billion ¥)
	$/kW			35.5

(continued)

APPENDIX A (continued) Part A

		MITSUBISHI HEAVY INDUSTRIES Kuretsu	BABCOCK HITACHI Tanashima	IHI* Isogo
5.2	ANNUAL COSTS, $	N.A.	N.A.	N.A.
5.2.1	Interest			
5.2.2	Depreciation			
5.2.3	Insurance and taxes			
5.2.4	Total fixed costs			
5.2.5	Labor and overhead Average man-hour cost cost/year			
5.2.6	Raw material breakdown			
	Unit cost			
	Annual cost			
5.2.7	Utilities, unit cost, annual costs			
	Electricity			
	Water			
	Steam			
	Fuel			
5.2.8	Maintenance cost/year			
5.2.9	Other costs, list			
5.2.10	Total variable cost/year			
5.2.11	Total annual cost			
5.3	WASTE DISPOSAL COST, $	N.A.	N.A.	N.A.
	Unit cost			
	Annual cost			
5.4	BY-PRODUCT CREDIT, $	N.A.	N.A.	N.A.
5.4.1	By-product 1			
5.4.2	By-product 2			

(continued)

APPENDIX A (continued) Part B

		BABCOCK HITACHI Takehara	MITSUI MIIKE MACHINERY Takasago	FUJIKASUI ENGINEERING CO. Kashiwa
5.2	ANNUAL COSTS, $	N.A.	N.A.	
5.2.1	Interest, %/yr			10
5.2.2	Depectation, %/yr			12.9
5.2.3	Insurance and taxes			None
5.2.4	Total fixed costs			$1 million (1.52 billion yen)
5.2.5	Labor and overhead			$6.67/man-hour (2000 yen/man-hour)
	Average man-hour cost cost/year			$0.11 million (33 million yen)
5.2.6	Raw material breakdown			
	Unit cost			a
	Annual cost			$54,000 (16.37 million yen)
5.2.7	Utilities, unit cost, annual cost			
	Electricity			$0.032/kWh, $2.99 million (9.8 yen/kWh), (987 million yen)
	Water			$0.038/m^3 $66,000 million (11.5 yen/m^3) (19.8 million yen)
	Steam			N.A. N.A.
	Fuel			b $2.07 million (625 million yen)
5.2.8	Maintenance cost/year			$563,000 (169 million yen)
5.2.9	Other costs, list			$110,000[c] (33 million yen)[c]
5.2.10	Total variable cost/year			
5.2.11	Total annual cost			
5.3	WASTE DISPOSAL COST, $	N.A.	N.A.	N.A.
	Unit cost			
	Annual cost			
5.4	BY-PRODUCT CREDIT, $	N.A.	N.A.	N.A.
5.4.1	By-product 1			
5.4.2	By-product 2			

APPENDIX A (continued) Part A

		MITSUBISHI HEAVY INDUSTRIES Kuratsu	BABCOCK HITACHI Tamashima	IHI* Isogo
5.5	NET ANNUAL COST		N.A.	N.A.
5.5.1	Cost for last year, mills/kWh	N.A.		
5.5.2	Cost at maximum continuous rating, mills/kWh			
5.5.3	Cost without FGD at maximum continuous rating, mills/kWh			
6.	ENERGY REQUIREMENTS, kW	N.A.		
	Pumps		4100	2000
	Fan		11,500	4800/unit
	Reheat		N.A.	N.A.
	Reductant chemicals		N.A.	N.A.
	Other		2000	1000
	Total (excluding reheat), kW	5070	17,600	7800/unit
	Per kWh of electricity	N.A.	0.015	N.A.

(continued)

APPENDIX A (continued) Part B

		BABCOCK HITACHI Tokohara	MITSUI MIIKE MACHINERY Takasago	FUJIKASUI ENGINEERING CO. Kashima
5.5	MEI ANNUAL COST	N.A.	N.A.	N.A.
5.5.1	Cost for last year, mills/kWh			
5.5.2	Cost at maximum continuous rating, mills/kWh			
5.5.3	Cost without FGD at maximum continuous rating, mills/kWh			
6.	ENERGY REQUIREMENTS			
	Pumps	1400	2800	4400
	Fan	3800	4200	3300
	Reheat	N.A.	N.A.	N.A.
	Reductant chemicals	N.A.	N.A.	N.A.
	Other	1300	1000	N.A.
	Total (excluding reheat)	8500	8000	N.A.
	Per kWh of electricity			

(continued)

APPENDIX A (continued) Part A

		MITSUBISHI HEAVY INDUSTRIES Kuratsu	BABCOCK HITACHI Tamashima	IHI* Isogo
7.	PERFORMANCE HISTORY: OPERATING PROBLEMS AND SOLUTIONS			
7.1	Scrubber system	N.A.	Scaling on plates solved by slurry spray. Strainer screen plugging solved by increasing screen area and slurry flow rate	N.A.
7.2	Demister	N.A.	Scaling solved by water wash	N.A.
7.3	Reheater	N.A.	Fall-off of refractory brick solved by changing the refractory	N.A.
7.4	Fan	N.A.	N.A.	N.A.
7.5	Sludge system	N.A.	N.A.	N.A.
7.6	Regeneration system	N.A.	N.A.	Unstable moisture content in gypsum. Controlled by control of slurry composition and mother liquors
7.7	By-product system	N.A.	N.A.	N.A.
7.8	Other	N.A.	N.A.	N.A.
7.9	Availability, %	100 cleaning, repair, etc. can be made during a scheduled shut-down of the boiler once a year for about a month	97.7	100

(continued)

APPENDIX A (continued) Part B

	BABCOCK HITACHI Takehara	MITSUI MIIKE MACHINERY Takasago	FUJIKASUI ENGINEERING CO. Kashima
7. PERFORMANCE HISTORY; OPERATING PROBLEMS AND SOLUTIONS 7.1 Scrubber system		N.A.	Scaling of upper scrubber was solved by sprays at top
7.2 Demister		N.A.	N.A.
7.3 Reheater		N.A.	Vibration of the combustion chamber at full load. Burner chips and fuel-air ratios were changed to correct this.
7.4 Fan		N.A.	None
7.5 Sludge system		N.A.	None
7.6 Regeneration system		N.A.	None
7.7 By-product system		N.A.	None
7.8 Other		N.A.	None
7.9 Availability, %		97	100 slutering machine stops every 2-3 months for a few days for maintenance. FGD system is then inspected.

[a]

Raw Material	Unit	Annual
$CaCO_3$	$0.0044/kg	$15,760/yr
$Ca(OH)_2$	$0.039/kg	$29,100/yr
H_2SO_4	$0.032/kg	$9,530/yr

[b] Fuel converter gas $0.021/1000 Nm^3 $1,550,000/yr
coke oven gas $0.047/1000 Nm^3 $526,700/yr

[c] Gypsum ($0.0055/kg, sales price $0.0037/kg, handling and transportation $0.0092/kg) annual cost $110,000.

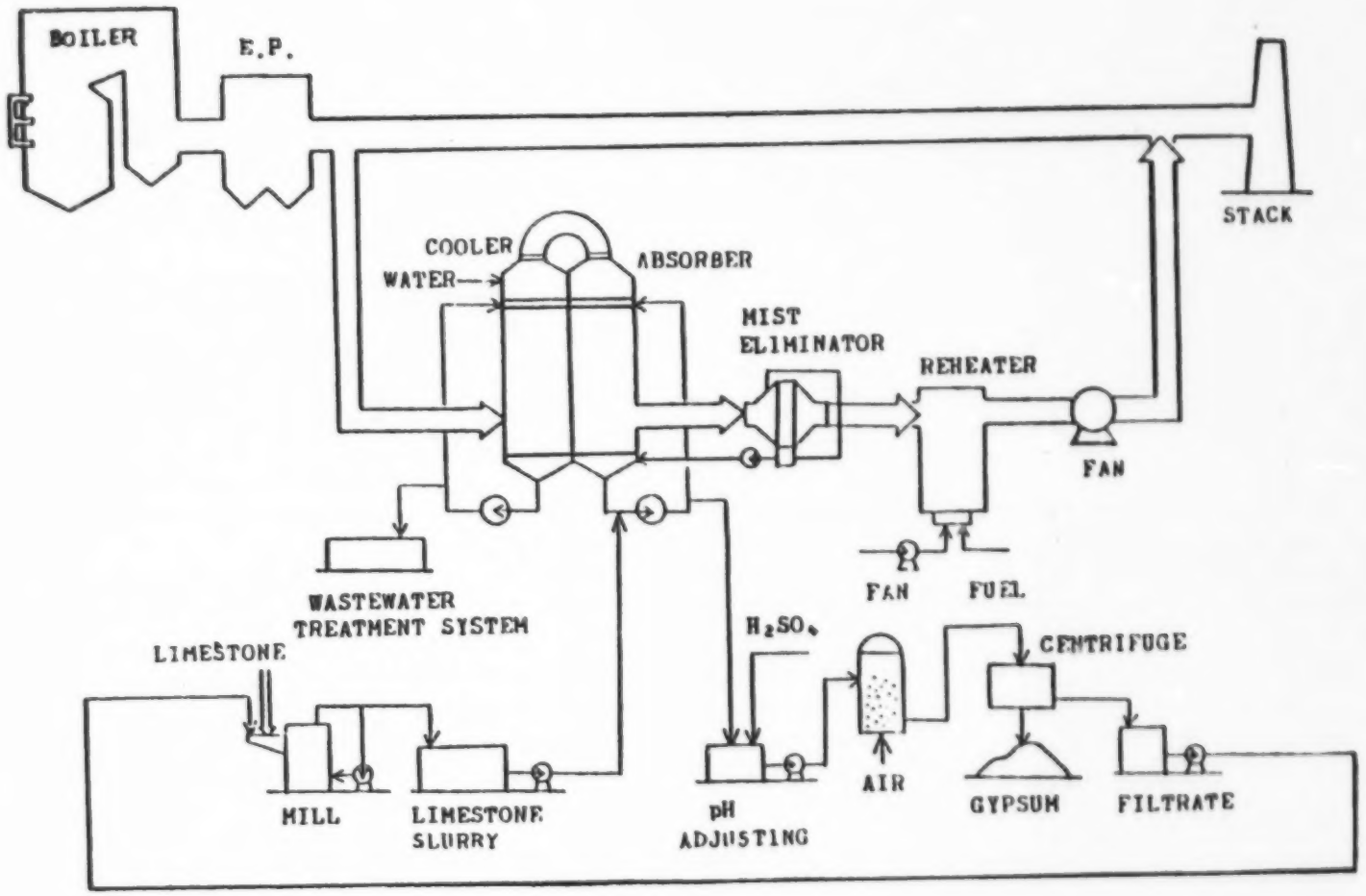

Figure A. Flowsheet of limestone gypsum process (MHI one-absorber system, Karatsu Station, Kyushu Electric)

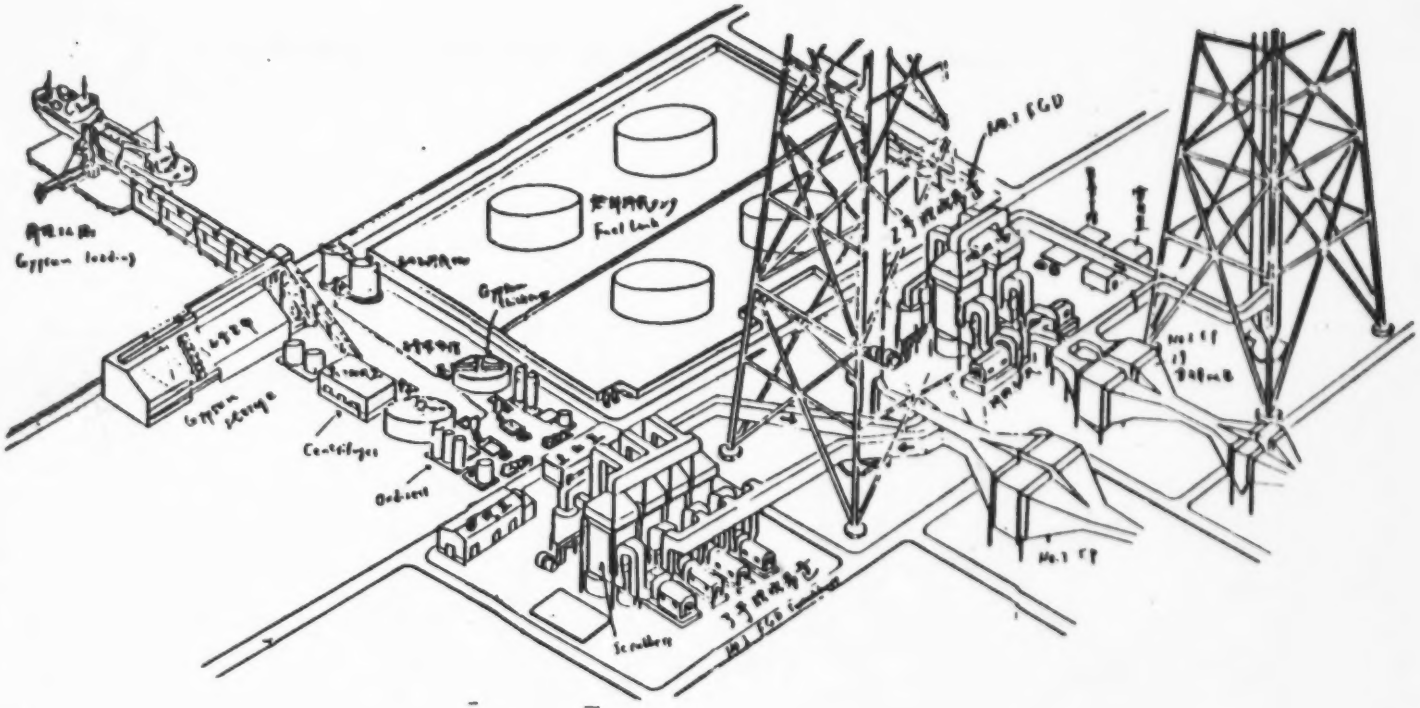

Figure B. Layout of Tamashima Power Station.

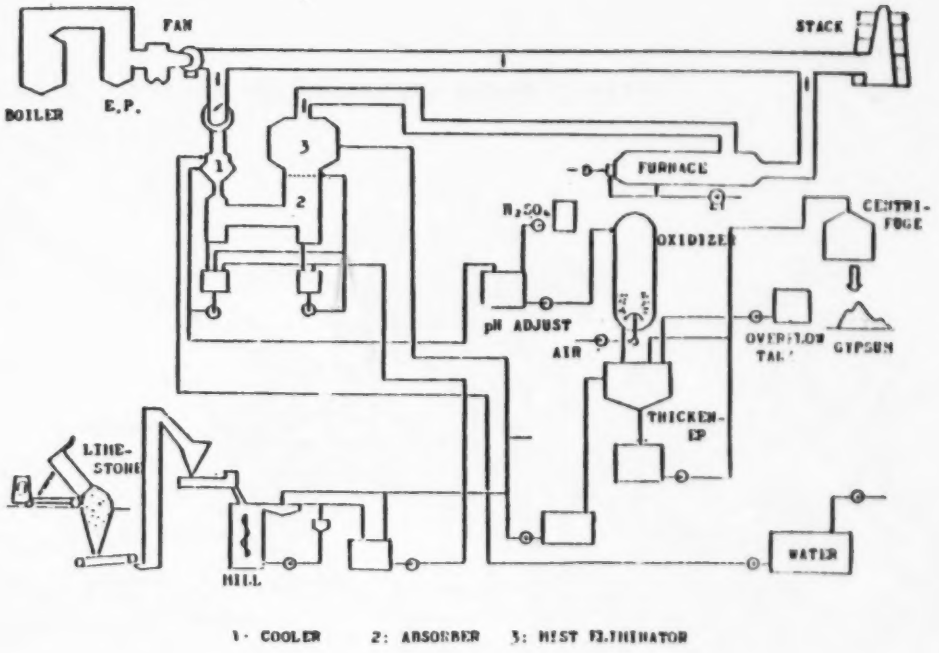

Figure C. Flowsheet of Babcock-Hitachi process.

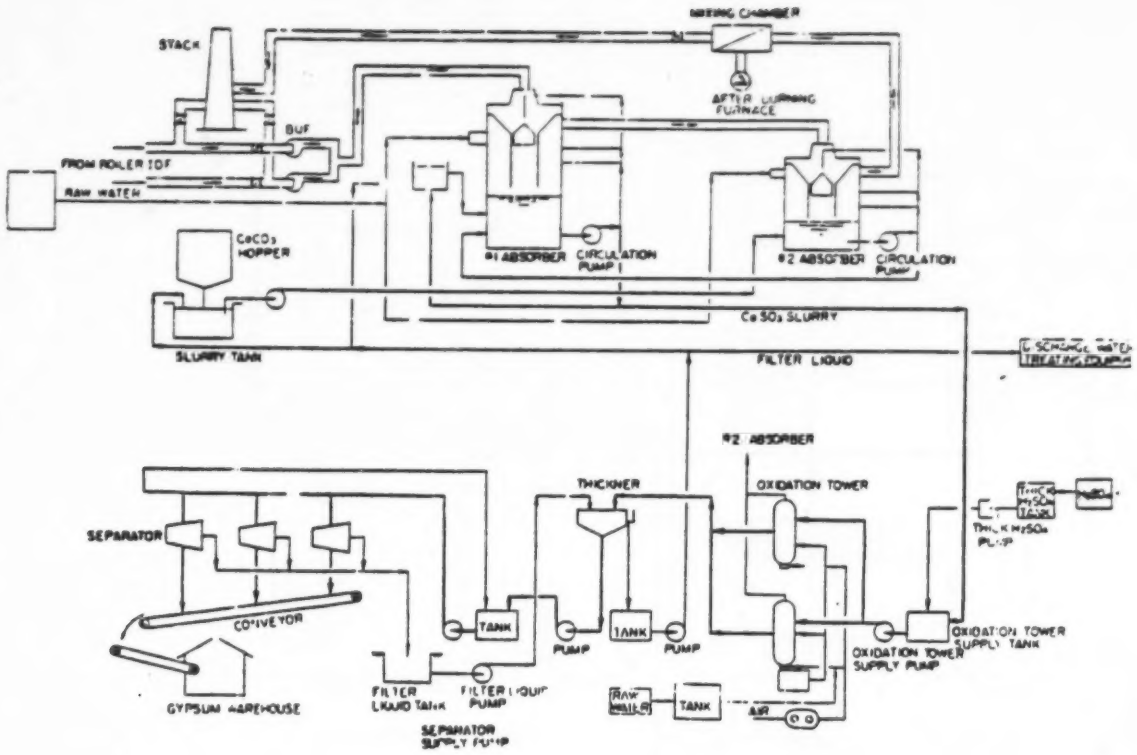

Figure D. Outline of SO_x removal plant
(Isogo Thermal Power Station)

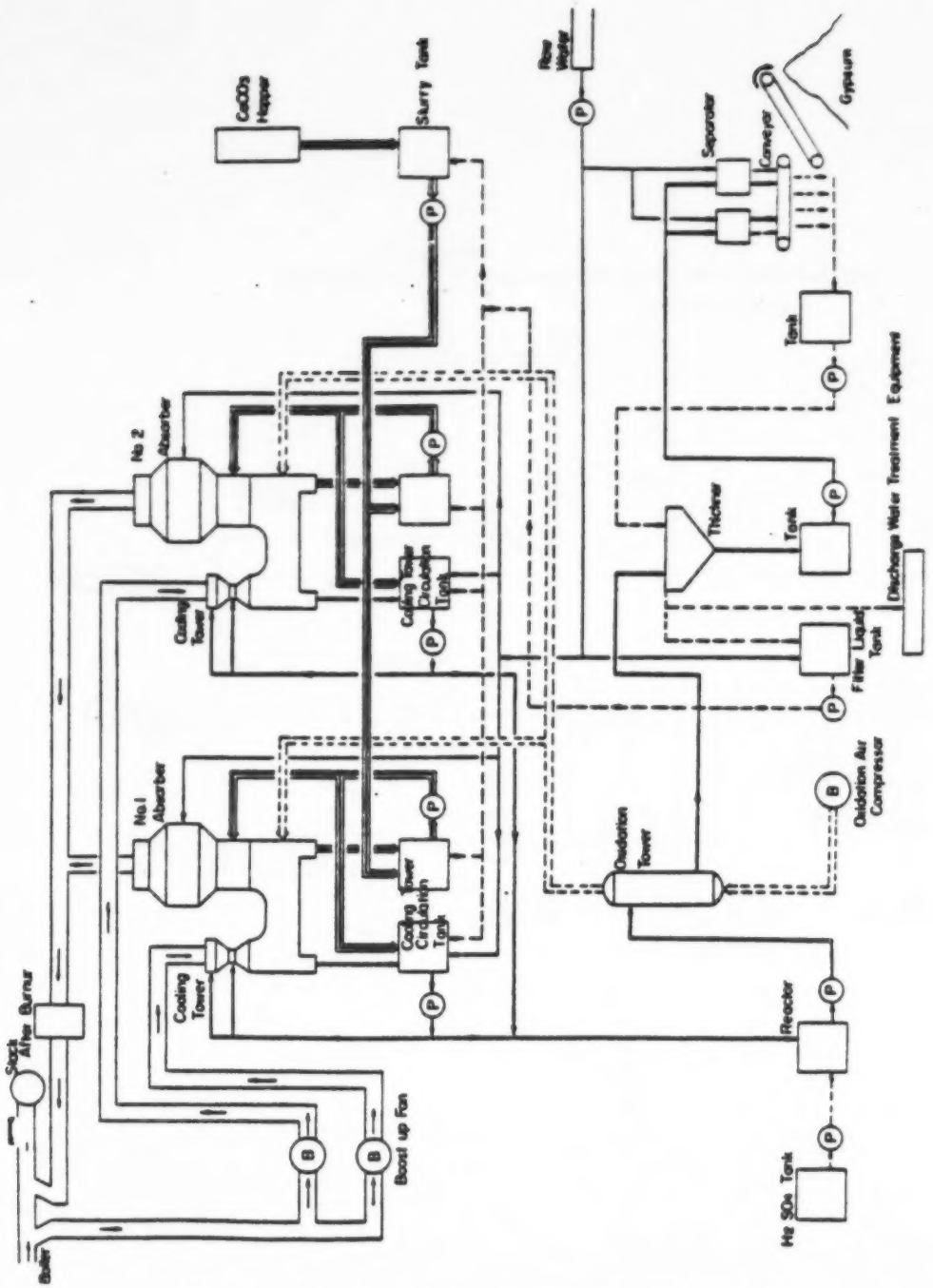

Figure E. Outline of SO_2 removal plant
(Takehara Thermal Power Plant)

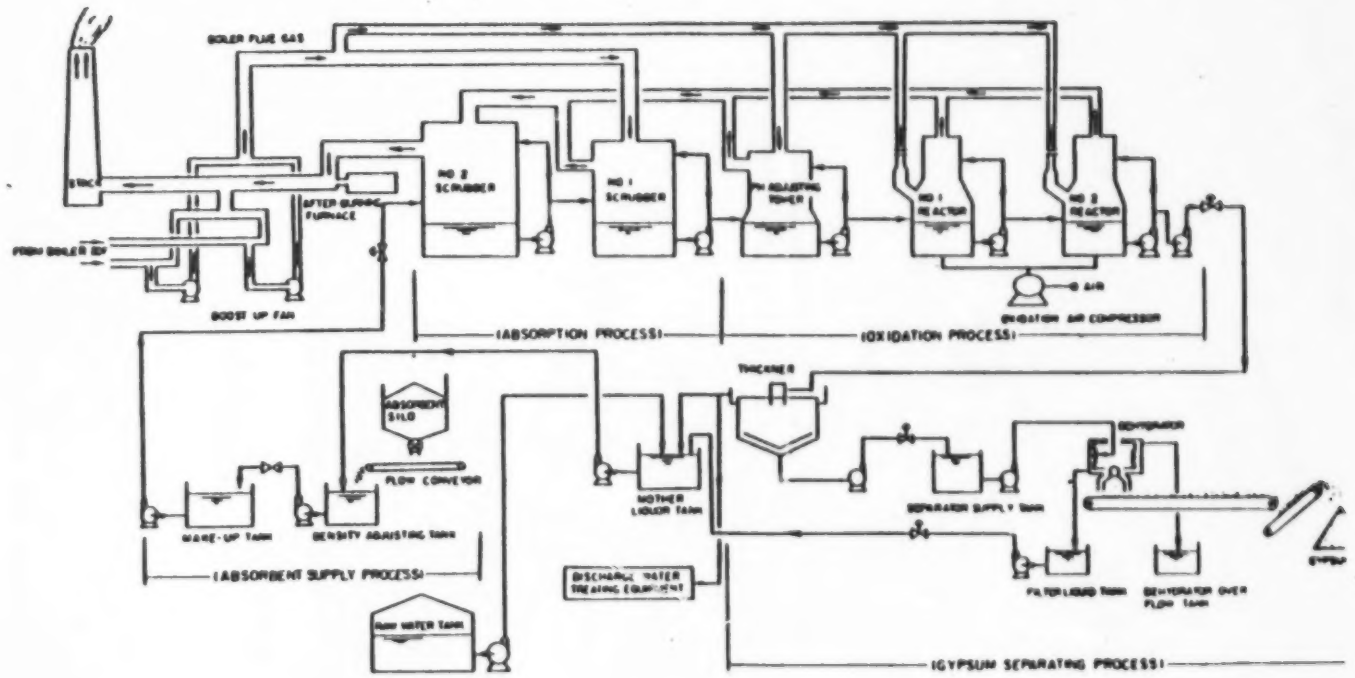

Figure F. Outline of SO_x removal plant
(Takasago Thermal Power Station)

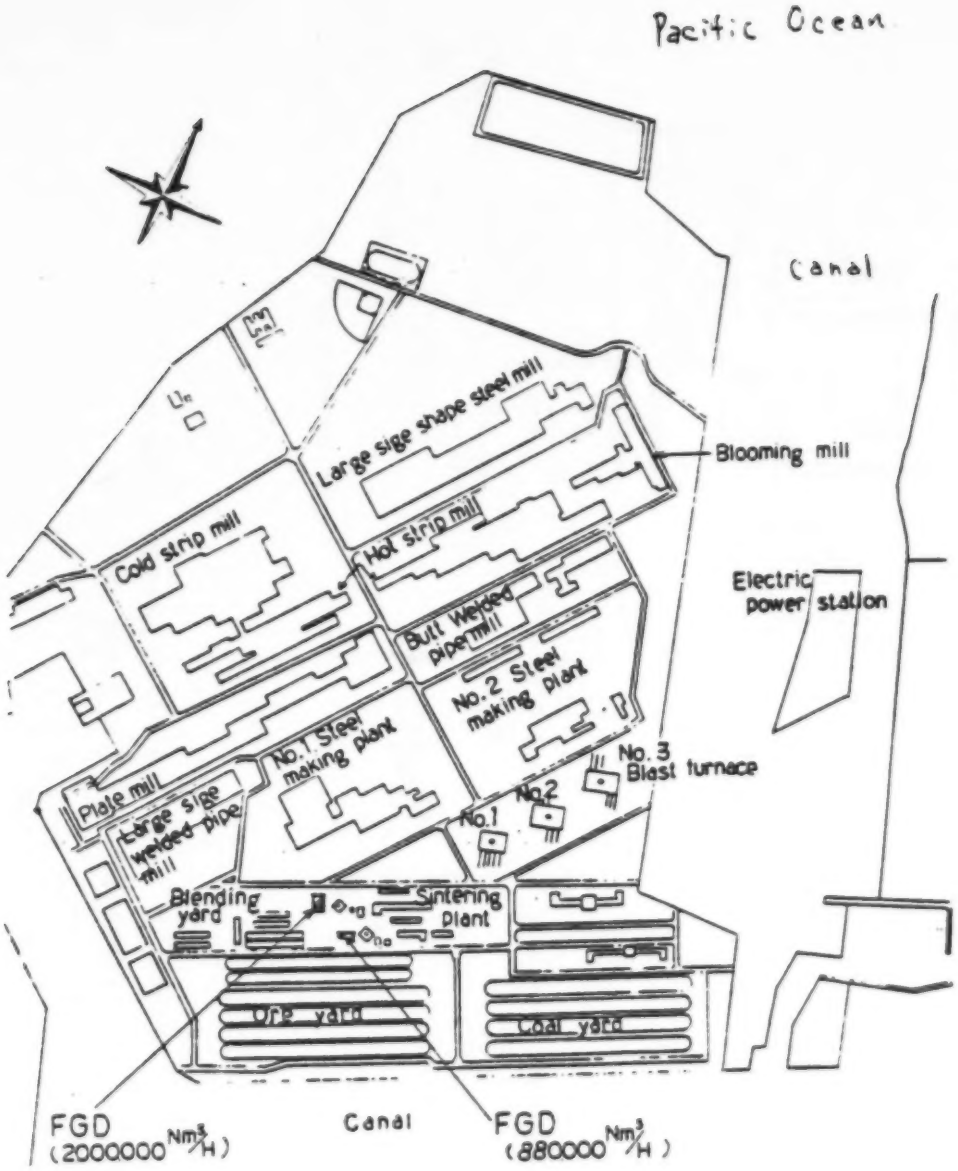

Figure G. Area surrounding FGD site in Kashima work.

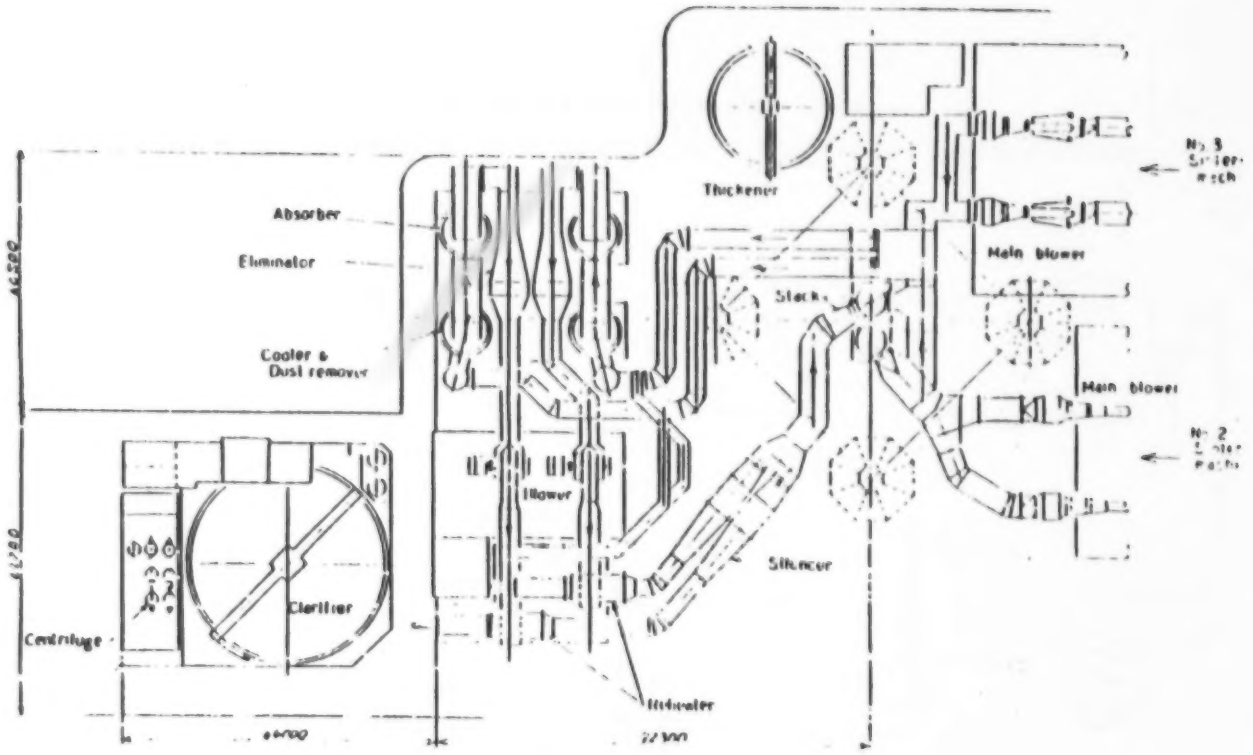

Figure H. Lay out of FGD for sintering machine.

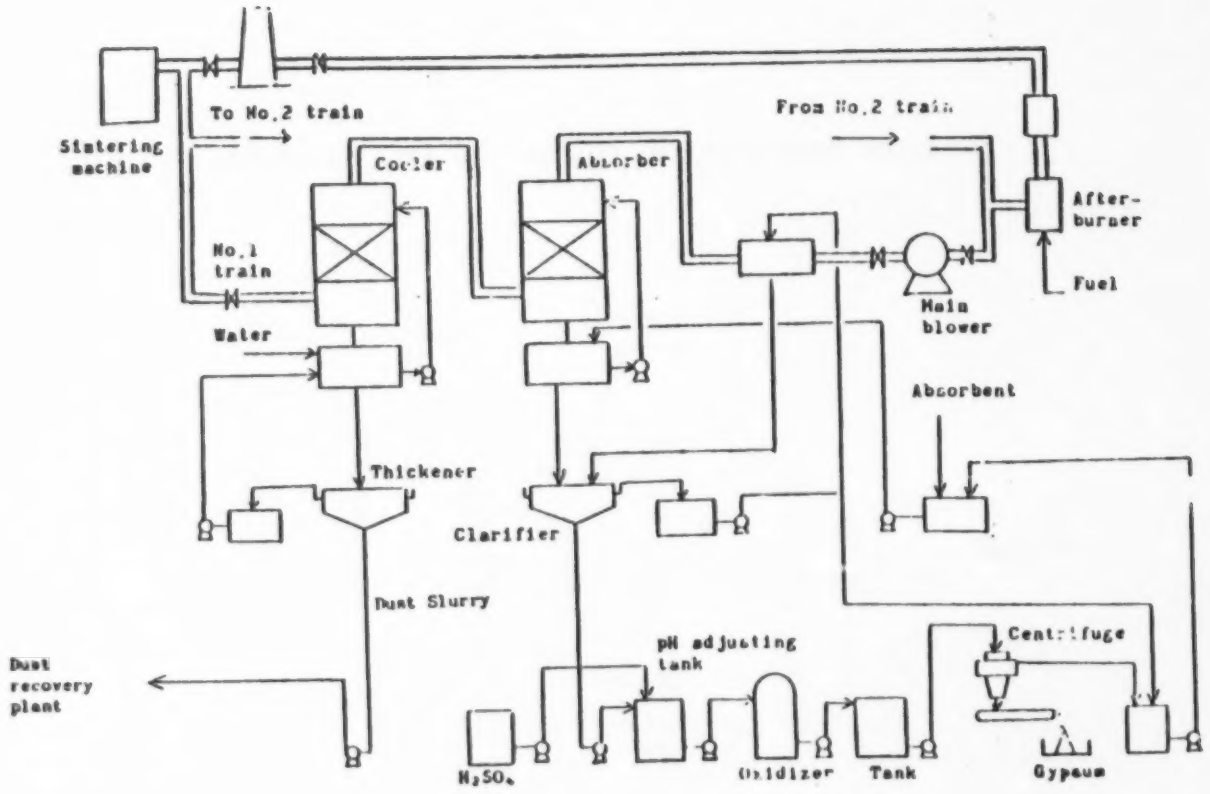

Figure I. Flowsheet of Moretana lime/limestone gypsum process (Kashima plant, Sumitomo Metal)

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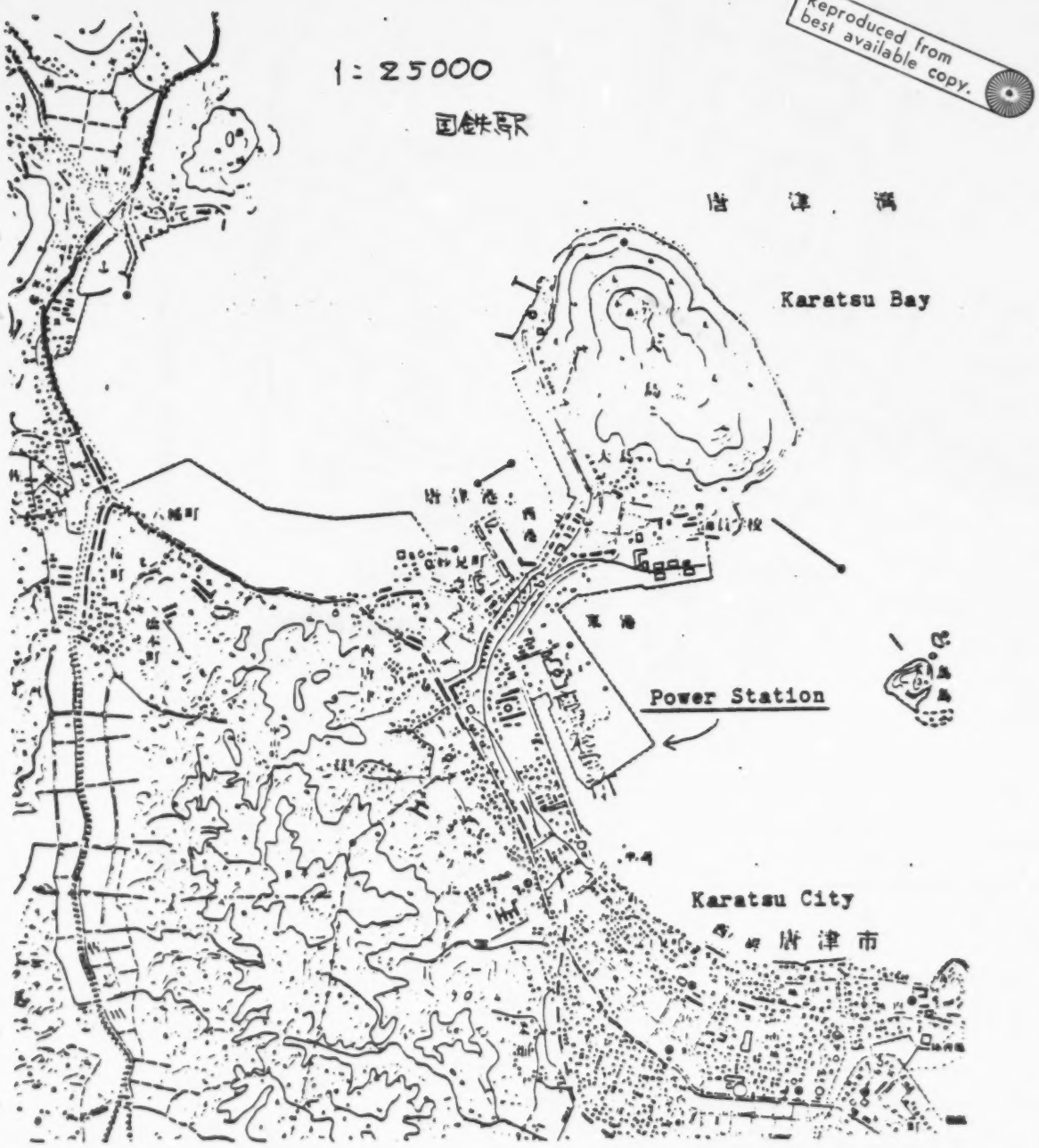

Figure J. Location of Karatsu Power Station.

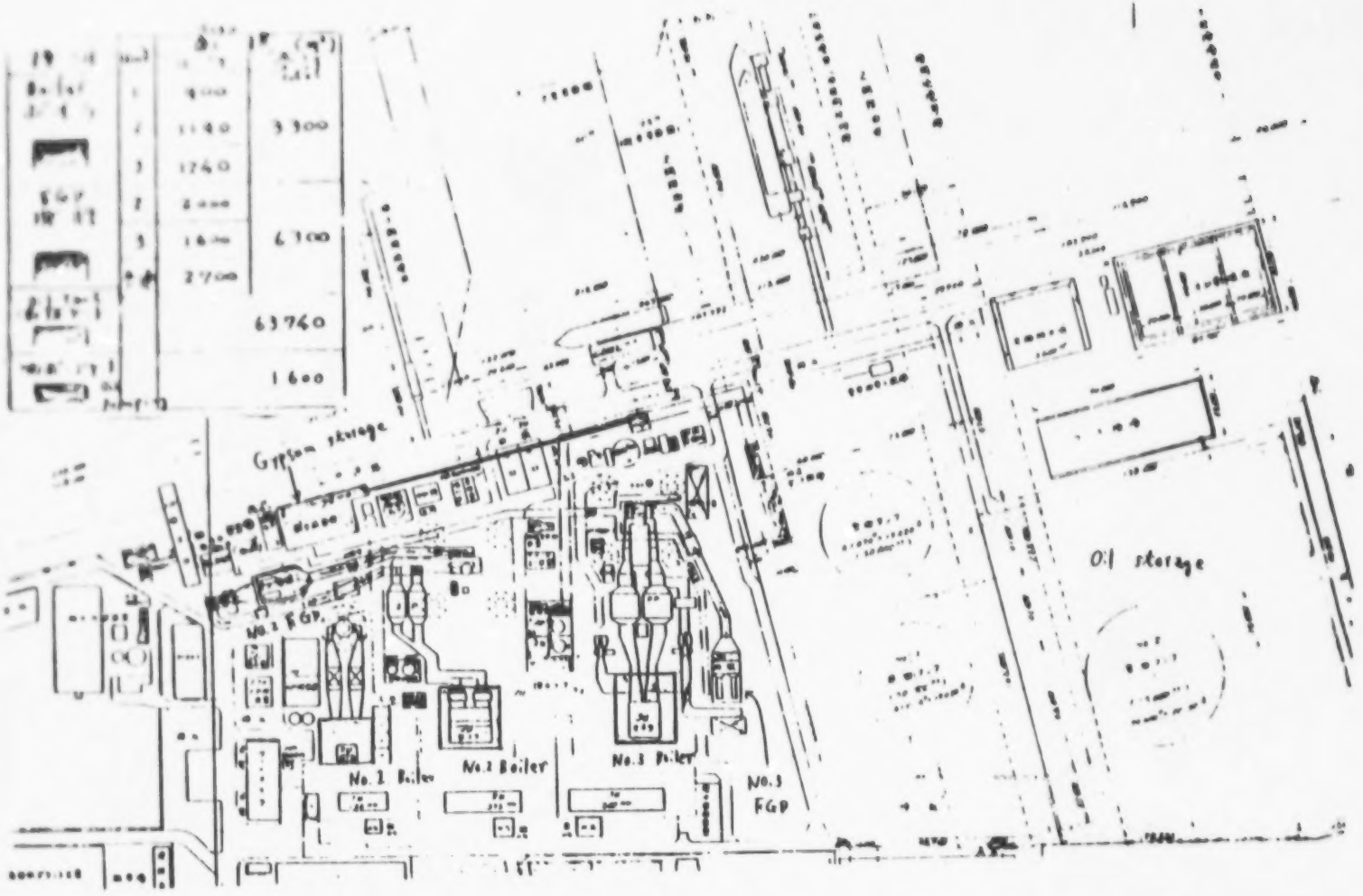

Figure K. Layout of the Karatsu Station.

APPENDIX B

APPENDIX B

Availability Factor Computation

1. Divide boiler capacity by the number of modules and obtain MW/module = x

2. Multiply boiler capacity by number of hours during selected period (MW) = a

3. Add all down times due to module trouble for all modules during selected period = b

4. Add all down times due to boiler trouble or reduction in electricity demand for all modules during period = c

5. Availability factor = $\frac{[a - x\ (b + c)]\ 100}{a - x\ c}$ = %

APPENDIX C

APPENDIX C. CONVERSION FACTORS USED IN THIS STUDY

Multiply	By	To Obtain
ft	x 0.30480	m
ft^3	x 28.317	liter
Btu/lb	x 0.55554	kcal/kg
	x 2.32593	kJ/kg
Btu/h	x $0.29300 \cdot 10^{-3}$	kW
acfm	x 1.6992	m^3/h
$lb/10^6$ Btu	x 1.80005	mg/kcal
	x 0.42993	mg/kJ
gal/min	x 3.78541	liter/min
	x 0.22712	m^3/h
gal/1000 ft^3	x 0.13368	liter/m^3
ft^3/min	x 1.6992	m^3/h
kcal	x 4.1868	kJ
kcal	x $1.163 \cdot 10^{-3}$	kWh
scfm	x 1.60776	Nm^3/h
gr/ft^3	x 2.288	g/m^3
gr/scfm	x 2.4182	g/Nm^3
in. H_2O	x 0.2488	kPa
in. H_2O	x 2.54	mbar
gr	x 0.0648	g
ton (short)	x 1.9072	metric ton

1 MW corresponds to 3200 to 3500 m^3/h flue gas (coal)

1 scfm = 28.317 l (60°F / 14.7 psia)
(15.5°C / 760.28 torr)

26.796 l (0°C/760 torr) = 0.026796 Nm^3

1 SO_2 = 2.927 g/liter

MW = electric power generated unless other wise specified